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ANALYSIS OF SPACECRAFT ONBOARD [U] COMPUTER PERFORMANCE

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GEMINI PROGRAM MISSION REPORT GT-3 [U]

Gemini 3

Supplemental Report 10

ANALYSIS OF SPACECRAFT ONBOARD COMPUTER PERFORMANCE [U]

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1.0 INTRODUCTION

This report presents an analysis of the spacecraft onboard-computer performance based on reconstructions of the ascent and reentry portions of the Gemini 3 (GT-3) mission. This report is a composite of the information contained in reports C.D. No. 3-260-6090, C.D. No. 3-260-6097, and C.D. No. 3-260-7001 prepared by:

International Business Machines Corporation
Federal Systems Division
Space Guidance Center
Owego, New York

These three documents contain plots of the reconstructed telemetry data as well as actual GT-3 flight data and are available upon request, from:

Gemini Program Office Files, GA
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

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2.0 GT-3 ASCENT POSTFLIGHT ANALYSIS

This section presents the results of the analysis of the performance of the spacecraft onboard computer during the ascent phase of the GT-3 flight.

The purpose of this study was to verify that no anomalies occurred in the computer or its program during the prelaunch and ascent phases of the flight and to analyze the inertial measurement unit (IMU) measurement error observed during the flight. An investigation of the nature of the error and its possible causes is documented in section 2.2 of this report.

This study was made using the Operational Program interpretive simulation which executes a Gemini computer program tape (magnetic) on the 7090 data processing system (DPS). The simulation uses fixed point arithmetic and Gemini word length. In addition, several associated simulation runs were made using an all FORTRAN model of the Gemini digital computer (GDC) ascent mode. These runs aided in the analysis of the IMU measurement error which occurred during the flight.

In the following sections, the implementation of the study and results are discussed, the conclusions reached are reported and recommendations are made.

2.1 Analytic Approach

This postflight analysis effort is based on reconstruction of the GT-3 flight which was accomplished by supplying actual gimbal angle and summed acceleration data taken from the flight telemetry to an interpretive simulation of the GDC program. In this manner, the performance of the onboard computer can be verified by comparing position, velocity and attitude error data obtained from the simulated GDC with corresponding telemetry data. Since actual flight data is used in the reconstruction simulation, the in-flight performance can be reproduced with a high degree of accuracy. The GDC interpretive simulation executes a Gemini magnetic program tape on the 7090 DPS. Use of the actual program permits verification of the performance of the computer mathematics with particular regard to parameter scaling, fixed point arithmetic, shifting and logic operations, and Gemini subroutine operation. This simulation, when supplied with actual acceleration and attitude information is a very useful tool for verifying GDC inflight performance.

Before attempting flight reconstruction, the telemetry data is manipulated in the following manner. The values of time, summed acceleration components, and gimbal angles are plotted against the telemetry frame number which is referenced to an arbitrary frame prior to platform release (umbilical disconnect). This procedure reveals any bad data points which are then corrected by replacement with data obtained from other telemetry stations. After correcting any bad data points, the intermediate values of time in the GDC which do not appear on telemetry because of transmission rate (one frame every 2.4 seconds) are reconstructed. This operation was automated on the 7090 DPS using GDC delta T information contained in reference 1. Special areas such as platform release, lift-off, stage II guidance initiate, and SECO countdown were reconstructed manually to obtain more detail in the flight profile. The result of these operations is a table of data which represents the flight profile. This table is then used to provide IMU inflight measurements and GDC clock times to the interpretive simulation.

At the beginning of each computation cycle the appropriate values of delta T, change in summed acceleration (three components), and gimbal angles are supplied to the simulated GDC program. If the computer time is one of the intermediate times which was inserted in the telemetry data, linear interpolation between adjacent telemetry frames is used to compute gimbal angle and summed acceleration data for the intermediate time. All parameters are treated in quantum form and remainders are saved to keep the reconstructed profile coincident with the flight profile.

Because no telemetry frames are generated between clock and accelerometer readings, the summed acceleration data is time correlated to within the accuracy of the telemetry time (15 msec). The simulated computer times were biased by approximately 7.6 msec to remove some of the error resulting from the telemetry time truncation. The gimbal angle information, to be strictly correct, is subject to time correlation using the flow tag data transmitted on telemetry. However, since the gimbal rates are in general small, no significant errors were introduced by assuming that the gimbal angles are associated with the time transmitted. For the same reason the errors introduced by allowing the angles to remain constant during the computation cycle are also small. The simulated GDC was also supplied with a platform release discrete, lift-off synchronization time and two azimuth updates.

In order to evaluate the effect of the IMU measurement error during flight, a separate FORTRAN flight simulation was exercised. Data for this simulation was obtained by comparing the IMU summed acceleration data with corresponding radar tracking data obtained from Space Technology Laboratories (STL). Manipulation of the differences in the acceleration profiles from these two sources resulted in an error characteristic for the IMU. The acceleration and gimbal angles measured by the IMU were then transformed through this error characteristic to obtain a flight profile more closely representative of the actual profile. This corrected profile was then used in a FORTRAN simulation of the GDC ascent mode to determine the effect of the error on inertial guidance system (IGS) guidance characteristics. The GT-2 postflight analysis report (ref. 2) demonstrated good agreement between the FORTRAN and interpretive simulations. Therefore, it was decided the FORTRAN simulation was adequate for this portion of the analysis.

Section 2.2 of this report contains a detailed discussion of the IMU error and the results obtained during this study.

2.2 Analysis of Ascent IMU Anomaly

This section deals with the analysis of the IMU anomaly which was experienced during launch. The various possible causes considered are discussed, the most probable cause is described, and finally a mission reconstruction was performed to evaluate IGS performance in the absence of the IMU anomaly.

2.2.1 Definition of Platform Anomaly.- The large pitch attitude errors which were obtained from the IGS late during stage II guidance made it evident that an excessive navigation error occurred during ascent. Preliminary analysis indicated the IGS radial velocity was considerably in error and subsequent analysis by Space Technology Laboratories (STL) supported this observation. Comparison of IGS summed acceleration and MISTRAM tracking data indicate that a +40 fps and a -125 fps error is present in the X and Z summed acceleration data following SECO.

The mission reconstruction, which is discussed in more detail later in this report, provided position and velocity comparisons at LO+360 seconds to within 75 ft and 0.4 fps on all axes. Thus it was concluded that the error was introduced prior to, or at, the IMU-digital computer interface. Furthermore, the correlation of the velocity errors on the platform X- and Z-axis rules out the GDC interface as a possible cause because common computer hardware is used to accumulate all accelerometer inputs. It was highly doubtful that the interface hardware could fail in such a manner as to produce a correlated error in the X- and Z-axis and virtually no error along the Y-axis.

The following factors were thus suggested as probable causes of the navigation error with the first being considered most likely:

(a) Excessive platform Y-gyro drift which results in a pitch down rotation of the inertial reference.

(b) Momentary pitch gimbal loop stabilization loss, perhaps due to a slip ring open, which results in a shift of 0.5° to 0.6° (pitch down) of the platform stable element.

The fact that a correlated error appears in the X- and Z-axis suggested that the inertial element had shifted or was drifting from its inertial reference and ruled out the possibility of large intermittent scale factor or bias changes in the IMU Z-accelerometer data.

The possibility of a temporary closure of the IMU orbit rate torquing relay was considered but was ruled out after inspection of the Y-gyro torquing current, which is monitored on telemetry.

Of the two possible causes listed above, the first is considered the most probable for the following reasons:

(a) Detailed analysis of the velocity error increase over several periods of time indicated a varying stable element misorientation was required to produce the error history (see fig. 2-1).

(b) The launch vehicle pitch rate between LO+190 and LO+330 seconds is 0.05 deg/sec or less. Thus, any sudden shift in the orientation of the stable element during this period of time should be seen as a rapid change in IGS measured pitch gimbal angle. Detailed inspection of this data in figure 2-2 will conclusively indicate that a sudden reference shift did not occur during this time interval.

The possibility of a reference shift occurring more slowly was also investigated. This was discarded because the IMU attitude malfunction circuitry would have detected the presence of significant errors between gyro and stable element orientation within 4 seconds.

(c) Detailed comparison of launch vehicle thrust attitude as computed by the General Electric (GE)/Burroughs system, and the IGS pitch gimbal angle history between LO+250 and LO+300 seconds indicates the presence of a platform pitch misorientation (see fig. 2-2). The radio guidance system (RGS) data plotted is basically the pitch attitude of the thrust vector, as computed in the RGS equations, corrected for the down range (central angle) traveled. Furthermore, this difference in vehicle pitch orientation seems to increase from 0.2° at LO+250 seconds to 0.6° at LO+320 seconds.

It was thus concluded that the IMU Y-gyro malfunctioned during the flight resulting in a pitch down rotation of the platform. To evaluate the rate and magnitude of this rotation, the Z-axis accelerometer error history was used in combination with the X-axis accelerometer data. Figure 2-1 presents the detailed method used to evaluate the orientation error. Note that three different smoothing intervals (5, 10, 15 seconds) were used in order to minimize the effects of noise on the data.

As is suggested in the figure, two platform drift rates are apparent, a pitch down drift of 33.4 deg/hr starting at 195 seconds, followed by a drift of 10.5 deg/hr starting at LO+243 seconds.

The accuracy of the above prediction was evaluated and the GT-3 mission was reconstructed using corrected summed acceleration and gimbal angle data. The results are discussed in the following section.

Additional support of the conclusions suggested above will come from detailed inspection and test of the platform as well as analysis of IGS performance during reentry.

2.2.2 Mission Reconstruction - Platform Data Corrected.- Figures 2-3 through 2-6 present the reconstruction results following removal of the suspected platform drift error. Recall from the previous section that the error being removed is a pitch down drift of the platform of 33.4 deg/hr between LO+195 and LO+243 seconds and a 10.5 deg/hr drift from LO+243 seconds through the end of flight.

Figures 2-3 and 2-4 present the effects of the drift error on the X- and Z-accelerometer data. Note in figure 2-3 that the drift rates assumed resulted in regeneration of the entire SFZ error history to within 4 fps. In figure 2-4 the contribution of the platform drift error to the SFX error, as determined by STL, is shown. Note that at SECO, 17.5 fps of the X-acceleration error is due to the platform drift hypothesized. Table 2-I presents the IGS position and velocity errors attributable to the simulated platform drift at several different times during flight. The magnitude of these position and velocity errors should readily emphasize the sensitivity of the IGS equations to navigation errors. Recall that the IGS pitch attitude error was limited at +6° from LO+290 seconds to SECO.

Figure 2-5 presents a history of the radial velocity generated during the reconstruction, which included correction for IMU drift. In figure 2-6 note the improvement in the agreement between the three-axis reference system (TARS) and the IGS attitude error following correction. The corrected IGS pitch attitude error reaches maximums of 2.7° and 2.2° at LO+300 and LO+330 seconds. These are largely the result of the scale factor and bias errors remaining in the IGS data. As will be discussed in a later section, errors of approximately 20 fps, 100 ft, and 15 fps in inertial velocity, radius, and radial velocity remain in the data following correction of gyro drift.

The most significant conclusions which can be drawn as a result of the drift removal and reconstruction are as follows:

(a) The drift hypothesized reproduces the STL SFZ error to within 4 fps.

(b) Removal of the drift error reduces the IGS pitch attitude error to a value less than 3° in the time period between LO+300 and LO+330 seconds.

(c) Removal of the drift error results in IGS system performance between 2 sigma and 3 sigma (see discussion of injection conditions, section 2.3.4).

2.3 Discussion of Ascent Flight Reconstruction

Several overall observations concerning the techniques used in reconstruction are pertinent. The first concerns the linear interpolation scheme used to derive data between data acquisition system (DAS) frames. While this technique is adequate for the purposes of navigation, figure 2-7 will indicate that the stage II guidance steering equations are extremely sensitive to the assumption. Observe that the inflight results are smoother than the reconstructed results. Further attempts at reconstruction should probably include some type of polynomial fit to the data in order to remove the apparent noise which is induced.

Secondly, additional attention should be given to time alinement of gimbal angle data, especially during periods of higher vehicle rates (0.5 deg/sec) because the attitude error traces indicate several areas where the inflight and the reconstructed attitude error traces differed by 0.2° to 0.5° (see section 2.3.1).

Finally, reconstruction of the intermediate computation cycle times should be done with the best accuracy attainable if position integration errors are to be avoided. Section 2.3.2 will indicate that the largest position difference obtained near SECO on the X-axis in the Operational Program was approximately 200 ft. It is felt that a considerable portion of this type of error will be eliminated with MF-3 MOD II (Gemini 4) because of the additional accuracy in the telemetered time-in-mode (t) parameter from the IGS.

In summary, it is felt that additional effort should be directed at improving the flight reconstruction in above areas in order to eliminate some of the differences seen between the inflight and reconstruction results.

The remainder of this section describes and explains the various data obtained from the flight and through reconstruction. It is divided into the following general areas of discussion:

(a) Gimbal angle and attitude error behavior.

(b) Position and velocity comparisons.

(c) Platform azimuth alinement.

(d) IGS injection conditions.

(e) Navigation accuracy.

(f) Insertion velocity adjust routine (IVAR) and incremental velocity indicator (IVI) operation.

(g) IGS discretes and lift-off synchronization.

Section 2.3.4 describes the predicted injection conditions that would have been achieved if switchover to the IGS had occurred on this flight. Section 2.3.6 describes the predicted effect of the IGS IVAR corrections. Section 2.3.4 contains additional detail on the differences in time between the RGS and IGS generated SECO discretes. The tail-off impulse deficiency measured on this flight is also discussed.

2.3.1 <u>Gimbal Angle and Attitude Error Behavior</u>.- Comparison of the tab lists and plots of the data derived from the flight and from the flight reconstruction revealed no significant differences in IGS attitude error.

Over the entire flight, the Operational Program simulation repeated the flight results to within 0.2°. The roll attitude error provided the only exception, and that was during the roll program due to slight differences in timing. Attempts at plotting the inflight and the reconstruction results on the same graph paper were abandoned because the results were practically identical.

It is suggested that section III-A of reference 2 be reviewed because many of the comments made in that section are equally applicable to this report. The following paragraphs will explain and discuss the characteristics seen in the roll, yaw, and pitch channels during the mission.

2.3.1.1 Roll Channel: At 10 seconds prior to launch, the roll gimbal angle was within one quanta (0.036°) of the angle desired by the IGS. Thus the initial estimate of platform misalinement as obtained from the gimbal angle data was +0.01°. Figure 2-8 compares the IGS and TARS roll attitude error throughout the launch.

Immediately following launch the roll error goes to +0.7° and the roll gimbal angle goes to 78.48° (see table 2-II). This effect is similar to that observed on GT-2 and is probably due to engine offset.

Inspection of the roll gimbal angle data (table 2-II) indicates that a 12.9° roll program was desired by the IGS and the magnitude of the roll maneuver as seen in the IGS roll gimbal angle data is 12.67°.

Between LO+20 and LO+150 seconds, the difference between the IGS and TARS error signals increases significantly. This is attributed to an approximate 40 deg/hr TARS roll gyro drift which is within specified 3 sigma (83 deg/hr) limits. The change or shift seen in the roll error at LO+80 seconds is due to the large yaw attitude change of the vehicle and the coupling of vehicle rates into the roll channel (see ref. 2, section III-A-1).

At LO+153 seconds the change in roll attitude error is due to stage I shutdown and the removal of the roll engine misalinement disturbing moment present in the stage I engines.

During stage II operation, the roll error increased a little over 1° indicating that the roll drift rate which was present in the TARS system during stage I had a reduced effect during stage II.

2.3.1.2 Yaw Channel: The inflight and the reconstructed yaw attitude error in figures 2-9(a) and 2-9(b) are practically identical.

The IGS yaw attitude error at launch is -0.1°. A slight buildup is seen in the differences between the TARS and the IGS commands between lift-off and LO+150 seconds. This is attributed to the roll error coupling into the yaw channel as the vehicle pitches over.

Between LO+40 and LO+100 seconds a definite tendency to limit cycle or oscillate is noted in the yaw attitude error data. The source of this oscillation is not known but it is worthy of additional investigation because it is evident in both the TARS and IGS error signals. A similar oscillation was observed during the GT-2 flight. Subsequent investigation by the Gemini launch vehicle contractor indicated this to be caused by wind shear effects.

Following staging the yaw gimbal angle changes from -1.48° to -0.04° responding to the effects of stage II engine and center-of-gravity offsets.

The primary system returns the vehicle to the proper yaw attitude as is evidenced by the yaw gimbal motion between LO+180 and LO+210 seconds.

The meaning of the near null, yaw attitude error during stage II guidance is very significant. The primary system which is controlling the vehicle is delivering a 1.5° to -1.0° attitude error signal from the TARS package during this period. This error signal is required to offset the effects of the center-of-gravity misalinement.

If the IGS were to control the vehicle, a similar attitude error would be required from the IGS system. Thus, if the IGS were performing guidance, the vehicle would assure a yaw gimbal attitude which would provide a similar error signal. The result of this would be a deficiency in out-of-plane velocity correction which has already been demonstrated in the GT-3 Performance Report (ref. 3). This deficiency has been corrected in Math Flow 6 which is scheduled to fly with Gemini V.

2.3.1.3 Pitch Channel: With the exception of the pitch gimbal angle change following stage II guidance initiation, the pitch gimbal angle behaved as expected.

IGS attitude errors obtained during stage I guidance were generally less than 3°. The deviations seen in the TARS and IGS error up to LO+150 seconds (see fig. 2-10) are attributed to drifts in the TARS package which put the vehicle on a high trajectory.

At 162.5 seconds the vehicle pitch rate is discontinued in the primary system. However, the IGS system continues the third pitch rate until guidance initiation, hence the IGS pitch attitude error increases to 2.1° during this period. At guidance initiation the IGS pitch attitude error increases to 22.7° reflecting the large vehicle pitch attitude correction being requested by the IGS system.

A fundamental difference in steering philosophy between the primary and backup system is evident here. Between LO+175 and LO+185 seconds the primary system pitches the vehicle at a maximum rate of -2 deg/sec, whereas the IGS is delivering a +6° attitude error to the vehicle. Had the IGS been performing guidance, the vehicle pitch rate may have assumed values as large as 9 deg/sec (based on autopilot gain constants) as the IGS maneuvered the vehicle to the proper pitch attitude.

In the period between LO+185 and LO+260 seconds the IGS error signal was less than 2° and within expected deviations.

The larger attitude error differences following LO+260 seconds can be explained by the errors in IGS position and velocity components. The IGS navigation components were corrected for the IMU drift error (see section 2.2.2) and the mission was reconstructed to evaluate the effects of the error on IGS commanded pitch attitude and attitude error (see table 2-III). AT LO+300 seconds it was determined that the commanded pitch attitude changed from -0.189 radians to -0.074 radians following correction. This reduced the IGS pitch attitude error at LO+300 seconds from 8.8° to approximately 2.8°.

Near SECO, the computations based on the corrected navigation components indicated the pitch attitude error was reduced from 12.6° to approximately 2.3°.

Inspection of table 2-III will indicate that at LO+300 seconds the error is large because of IGS sensitivity to attitude (measuring) errors and at LO+330 seconds the IGS is sensitive to radial velocity measurement errors. Observe that at LO+300 seconds the altitude and radial velocity differences in the table are approximately 2100 ft and 62 fps, respectively. AT LO+330 seconds the same differences are approximately 5000 ft and 120 fps.

From table 2-III the conclusions can be drawn that removal of the IMU drift anomaly will reduce the IGS pitch errors to acceptable limits.

2.3.2 Position and Velocity Comparisons.- Table 3-IV compares the inflight DAS navigation data with similar data derived from mission reconstruction.

Inspection of this data indicates that a bit-for-bit comparison was not obtained in either case nor is it immediately obvious that one simulation provides a better reproduction of the flight than the other.

The largest position differences between the flight results and those obtained through reconstruction is seen in the X-component of the Operational Program run (200 ft at LO+355 sec). Inspection will show that the Operational Program result is within 25 ft of the FORTRAN result. The majority of the 200 ft difference is attributed to DAS time quantization (25 300 fps × 0.015 seconds = 380 ft). Note that IGS time is biased 7.6 msec in the reconstruction so as to minimize this type of error. That explains why the reconstruction data X-position is larger than the corresponding inflight data.

The reconstructed velocities, in all cases, are within 0.4 fps of the flight values. The effects of the azimuth update on the position and velocity data can also be found in the table. The most significant increase in differences is noted on the Z-axis where the Operational Program difference increases to 0.30 fps. However, it is felt the repeatability is excellent considering the fact that any navigation error is interpreted as a platform misalinement and used to recompute the initial navigation conditions.

The reasons why a bit-for-bit reconstruction of the flight data was not obtained are many. Several of the more significant factors will be discussed; however, the fundamental limitation is in the telemetry area, in that all the inputs to the IGS are not monitored. The data which was not available thus had to be reconstructed and supplied as an input to the Operational Program. This analysis used linear interpolation between data points, and as exhibited in the stage II pitch attitude error, a more sophisticated fit should be used which will remove the apparent noise induced by linear interpolation.

The second assumption used in this analysis is that all telemetry data is valid at the telemetered time from lift-off in the ascent mode. This assumption is acceptable for the summed acceleration data, but the gimbal angles, velocities, positions, et cetera, all require special treatment (time tagging) in order to conform with the time from lift-off time base.

A third factor is the accuracy to which computation cycle times can be reconstructed. Failure to reconstruct the time of each computation cycle exactly will also frustrate attempts at bit-for-bit repeatability.

The manner in which the DCS constants are loaded into the simulation also contribute slightly to the differences. The DCS parameters were loaded in decimal and following conversion to octal it was noted that they differed from the octal value loaded for flight in the least significant bit.

In summary it is felt that bit-for-bit repeatability under the pre-ent set of circumstances would be rather difficult to achieve, and certainly would require a considerable amount of time and manpower to overcome some of the obstacles mentioned above.

It is felt that both the FORTRAN and the Operational Program results produced acceptable reconstruction of the flight parameters and it is thought that a limited amount of effort in the area of filtering, or smoothing the data and intermediate computation cycle reconstruction would result in a reduction in the differences noted.

The decision as to whether a FORTRAN or Operational Program simulation should be used for flight reconstruction is probably somewhat arbitrary in terms of the type of repeatability obtained. Certainly either simulation would point out any significant GDC errors should one occur during flight. The real problem might rest in the diagnosis of what IGS logical operations failed and at what point in time.

Although there is good agreement between the accuracy of FORTRAN and Operational Program reconstruction, there are other reasons which make it more desirable to use the Operational Program for performing any further reconstruction.

Among the more significant reasons is the fact that if there is a scaling error, the FORTRAN will never show this. The Operational Program simulation readily identifies this fact and prints it out on the output listing telling the exact computation which has overflowed. This phenomena has been consistently noted in our Operational Program preflight simulation where FORTRAN will work for any range of variables because it is in floating point arithmetic whereas the Operational Program failed under certain conditions.

Another reason for using the Operational Program is that it contains a great deal of detail logic which is not in the FORTRAN mechanization of the equations. Any failure in this detail logic will not be detected by a FORTRAN reconstruction. This is especially true with respect to the various subroutines such as MDIU, DCS, DAS, TRS, Sin-Cos, Tan^{-1}, Square Root, Table Look-Up, Polynomial Solution for Reentry, Log, Error Angle, Gimbal Angle, Angle Limiting, Root Sum, Accelerometer, Clock, Frame Change, Ladder Output, Go--No-Go, AGE, and Rendezvous Radar Smoothing and Table Storage.

These two items are felt to be a significant reason for mission reconstruction using the actual program which flew, although it might be desirable to perform the preliminary reconstruction with FORTRAN to get a feel for the accuracy of the guidance and navigation computations.

2.3.3 Platform Azimuth Alinement.- Reconstruction of the in-flight DAS data indicated that the platform roll gimbal angle, at the time of platform release, was within one quanta (0.036°) of the value desired by the IGS. The value read by the GDC was 77.796 (2161 quanta) and the commanded roll gimbal angle was 77.786°.

The inflight results indicated both azimuth updates were received and properly used by the GDC. Table 2-V lists the platform azimuth alinement values obtained from the reconstructions. The difference in misalinement estimates after the 140-second update is less than 9 arc seconds and would contribute less than a 1 fps out-of-plane velocity difference at SECO.

It is significant to note that a platform misalinement of -0.52° (31.2') was computed as a result of the airborne azimuth updates even though the platforms' roll gimbal orientation at platform release was set to within 0.01° of the value desired. This would tend to indicate that the buildup of platform azimuth orientation errors from the launch pad thrust mount, up through the launch vehicle and spacecraft to the IMU and into the stable element was near the expected 3 sigma limits.

The following error sources and contributions were used to define the expected 3 sigma azimuth alinement accuracy for this flight:

	Source	Arc minutes
(a)	Launch pad thrust mount orientation[a]	±12
(b)	GLV to thrust mount alinement[a]	± 3
(c)	GLV twist[a]	±32
(d)	GLV/SC mechanical interface	-
(e)	IMU to SC alinement	± 6.1
(f)	Cube to IMU case alinement	± 1.6
(g)	Resolver to C.O.D. error	±10
	RSS Total	±36.3

Note that ARU readout and alinement errors are not included above since the roll angle as read by the GDC was within 0.01° of the value desired. Observe that although the inflight determined misalinement is within the 3 sigma limit, the table does indicate that substantial alinement errors are required prior to the spacecraft interface to produce the results obtained during flight.

2.3.4 IGS Injection Conditions.- Table 2-VI presents the IGS measured injection conditions obtained during the flight and those obtained via reconstruction. For additional comparison the suspected platform drift error was removed from the accelerometer data and an additional reconstruction performed. These results are listed in the table in column 3. Column 4 lists the quoted insertion conditions obtained from the flight for comparison with the IGS results.

In particular note the differences between the quoted and the IGS flight values of velocity, altitude, and radial velocity. A similar comparison of the quoted values and the IGS corrected (column 3) data will provide an indication of the effects of the IMU anomaly on IGS navigation. Observe that the differences indicated between columns 3 and 4 would suggest that the IGS navigation errors were within 2 sigma in the absence of the platform anomaly.

Had a switchover to the IGS been accomplished early during flight, it is thought that the IMU anomaly would have resulted in the following conditions at SECO + 20:

---

[a]Martin Company Report WGD-70, Misalinement of GLV/SC Interface from 85°, dated Jan. 30, 1964.

V = 25 657 fps

R = 21 429 800 ft

Γ = -0.33°

V_P = -147 fps

All of the above numbers are based on the perturbations suggested by table 3-VI. The injection condition would result in lowering perigee approximately 46 000 ft and apogee approximately 10 000 ft.

It is thought the IVAR corrections following insertion would be approximately +17 fps since the velocity magnitude measured in the IGS would be some 17 fps short of the targeted value because of the deficiency seen in cut-off impulse (I_{co}) during flight. The IGS-measured radial velocity and altitude would be approximately equal to the values desired since the IGS was doing guidance. Applying the 17 fps correction would raise perigee approximately 6000 ft and apogee by 50 000 ft, resulting in a final orbit with apogee 40 000 ft higher and perigee 40 000 ft lower than that targeted.

Comparison of the predicted trajectory conditions with the go--no-go criteria at insertion suggests that the spacecraft orbit would have resulted in a go condition.

2.3.5 Navigation Accuracy.- The data which is used to support and justify the statements contained in this section was obtained from the STL analysis of the IMU tracking errors.

It is noted that the IGS performance was outside predicted 3 sigma values because of the IMU gyro drift anomaly experienced during flight. STL analysis indicated IGS X- and Z-axis velocity and position errors to be +40 fps, -125 fps, +1000 ft, and -8000 ft, respectively at SECO+20.

Correcting the IGS accelerometer data for the IMU gyro drift anomaly resulted in IMU performance which was within 2 sigma of the expected results (see previous section and table 2-VI).

The out-of-plane velocity computed by the IGS performed excellently. The errors were within 1 sigma. The out-of-plane velocity at SECO+20 also demonstrated the operation of the IGS/RGS azimuth update equations, with the airborne updates correcting for 0.52° of platform azimuth misalinement.

2.3.6 IVAR and IVI Operation.- Verbal reports of the IVI readings following SECO+20 correlate well with the results obtained via postflight reconstruction. Table 2-VII contains a sequential list of IVI and flight director indicator (FDI) readings which were obtained in the FORTRAN reconstruction. The Operational Program reconstruction produced almost identical results. Comparison of the FDI readings tabulated with those obtained via inflight DAS also resulted in a good agreement.

A sample V_{ga} calculation is included below in order to illustrate why the IVI readings were small in relation to the velocity errors in the Y-computational axis:

$$V_{ga} = (V_R)^2 A_5^* + V_F - V + (R - R_F) A_7^*$$

where: at LO+364.9 seconds

V_{ga} = Horizontal velocity to gain to reach apogee

V_R = Radial velocity (147.3 fps)

V_F = Targeted velocity (25 699 fps)

V = IGS measured velocity (25 702.6 fps)

R_F = Targeted altitude (21 437 800 ft)

R = IGS measured altitude (21 449 153 ft)

A_5^* = Radial velocity perturbation coefficient (-0.0004243 sec/ft)

A_7^* = Radius magnitude perturbation coefficient (-0.000898 fps/ft)

Substituting in the above equation results in

$$V_{ga} = -24 \text{ fps}$$

Thus at LO+364.9 seconds, the IGS indicated a velocity reduction of 24 fps was required to correct the apogee altitude. The individual contributions due to radial velocity, velocity magnitude, and attitude error were 9.2, 4.6, and 10.1, respectively. Of particular significance is the fact that the horizontal velocity correction, required to compensate for the 147 fps radial velocity error, is only 9.2 fps.

An analysis was done to determine the potential effects of the IGS-IVAR corrections had they been applied to the spacecraft. At LO+372 seconds it was noted that the IGS indicated 28 fps should be subtracted from the spacecraft's velocity to correct apogee. During the separation maneuver, 10 fps is normally added; so, effective reduction of insertion velocity is 18 fps. Thus 18 fps would have been subtracted from the spacecraft, lowering the apogee by 9 n. mi. Had the indicated perigee correction (V_{gp} = 6 fps) been applied at apogee, perigee would have been raised 3 n. mi. The operational and the FORTRAN reconstructions indicated time-to-apogee (T_{AP}) was LO+2562 and LO+2561 seconds, respectively.

2.3.7 <u>IGS Discretes and Lift-off Synchronization</u>.- Table 2-VIII presents a list of the various discrete events issued or controlled by the IGS. Table 2-IX presents a detailed breakdown of the IGS data used to assess computer lift-off synchronization. Detail is provided which defines how this data is used and what assumptions were made in the determination lift-off synchronization. The analysis indicated lift-off sync was obtained 2 msec late and the uncertainty on this number is $\pm$15 msec.

The IGS indicated value of SECO time was LO+333.628 seconds. It is understood that a discrete measurement on telemetry indicated this discrete came up at LO+333.618 $\pm$ 0.1 seconds. Off-hand, the two numbers are incompatible. Two situations are suggested which could cause this incongruity. The first is the accuracy of the 333.618 second figure. Perhaps this quantity must be biased in the other direction, that is, LO+333.618 (+0.100, -0.000) seconds. The second situation would be a slight error in the IGS clock such that the GDC is running ahead of real time. The type of error the incongruity suggests is approximately 10 msec. The accuracy of the GDC clock is such that a 20 msec error might be obtained after 330 seconds of operation (60 ppm $\times$ 330 seconds).

It is understood the RGS SECO was generated at LO+333.727 seconds. Let us now explore whether the 333.628 figure suggested by the IGS is reasonable. First of all, it is noted that the IGS suffered from a navigation error of +16 fps (velocity magnitude, see table 2-VI) which would account for 66 msec of early delivery. Secondly, the IGS t_k (SECO time bias) constant contains a correction of 16 msec to account for expected navigation and guidance errors. The situation normally expected is one where the IGS measured velocity is approximately 3 fps short of what is actually achieved. Thus the IGS SECO discrete is delivered early to account for this potential error. This is added to the 66 msec figure. The remaining difference in SECO generation could be attributed to the uncertainty in delivery of the discrete, $\pm$22 msec based on a 44 msec fast loop duration during the SECO countdown.

Figure 2-11 plots the GDC velocity magnitude following SECO from the corrected FORTRAN run. This plot will be used to support the conclusion that a velocity deficiency occurred in cut-off impulse (I_{co}). The corrected FORTRAN run data is being used because removing the effects of the platform drift anomaly presents a better estimate of the actual insertion conditions. It is felt that, although a certain amount of measurement error still remains in the data presented, it will not affect the conclusions reached.

Note on figure 2-11 that IGS measured velocity at LO+333.660 seconds is 25 702.63 fps. Also at SECO+20, the velocity is 25 702.22 fps. Because of the proximity of the vehicle to perigee at this time, the only parameter affecting the velocity magnitude is thrust acceleration. Thus, over the above time interval, it is noted that a 99.59 fps impulse can be attributed to thrust acceleration.

We now considered the fact that the primary system issued the SECO discrete at LO+333.727 seconds. The expected impulse following this time is equivalent to 0.445 second of engine operation (0.427 engine impulse +0.018 second GLV relay delay). The separation in time between the point where the IGS read the accelerometers and the point where the RGS delivered the SECO discrete is 0.067 second. Thus the expected IGS measured impulse from LO+333.660 seconds to SECO+20 is equivalent to 0.512 seconds (0.445 + 0.067) of engine operation.

Assuming thrust acceleration of 240 fps^2 near SECO, one would then expect a measured ΔV of 123 fps. As already pointed out, the actual measured ΔV was only 99.6 fps. Thus it is concluded that the measured impulse is far short of what was actually expected. A deficiency equivalent to 100 msec of engine operation is suggested by the above data. This of course implies that IGS time over this interval (time as determined by the IGS clock) has no errors. Correcting IGS time to reduce this deficiency would further aggrevate the inconsistency. It is suggested that this whole area be further investigated in order to identify IGS/real-time synchronization errors and the actual deficiency in I_{co}.

2.4 Conclusions

The following conclusions are formed based on the analysis performed and documented in this report:

(a) No discrepancies can be found in the operations of the Gemini digital computer (GDC) or its output during the ascent portion of the mission.

(b) A significant navigation error was introduced by an IMU anomaly during the mission. This anomaly is thought to be a malfunction in the platform Y-gyro which results in a pitch down of the inertial element. The platform drift rates are predicted to be as follows:

33.4 deg/hr from LO+195 to LO+243 seconds.

10.5 deg/hr from LO+243 seconds through SECO.

(c) Removal of the above IMU anomaly from the IGS data, and subsequent reconstruction of the mission indicated the IGS system navigation errors would have been less than 2 sigma in the absence of the IMU anomaly.

(d) The IGS pitch attitude error under the above conditions would have been less than 2.7° at LO+300 seconds.

(e) The position and velocity data obtained during flight was reconstructed to within 200 ft and 0.4 fps.

(f) Behavior of the IGS attitude error signals was in general duplicated to within 0.2°. The limited IGS error signal following LO+290 seconds is attributed to the IMU anomaly. Removing the anomaly from the IGS data results in a maximum IGS computed pitch error at LO+330 seconds of +2.7°.

(g) The IGS was successful in accepting the airborne azimuth updates and reducing what could have been a potential 200 fps out-of-plane velocity error to one less than 5 fps. The calculated platform misalinement on this flight was on the order of 0.5°.

(h) Reconstruction of the IGS operations in the IVAR area indicate that good agreement existed between the airborne values noted and the reconstructed values.

(i) Error in IGS insertion condition with and without the IMU anomaly are as follows:

	With anomaly	Without anomaly
V, fps	13	20.55
R, ft	7000	-28
V_p, fps	140.0	11.38
Γ, deg	0.3123	0.0432

The numbers quoted above, without anomaly, do include the remaining scale factor, bias, alinement, and drift error. Only the Y-gyro drift was removed from the accelerometer data prior to reconstructing the mission.

(j) The IGS data indicates lift-off synchronization was established late by approximately 0.002 second.

(k) The 100 msec separation between the RGS and IGS issued SECO discretes is attributed to the IGS navigation error.

(l) IGS velocity data following SECO supports the conclusion that a 100 msec deficiency was measured in stage II engine cut-off impulse.

2.5 Recommendations

The analysis performed did not result in any recommendations in the GDC area or its program; however, the following recommendations are made in the IMU area:

(a) Review IMU test history to evaluate whether any data or evidence was available prior to flight concerning the impending malfunction.

(b) Review component test history to determine whether the component was exposed or subjected to some operation or event which could have contributed to the malfunction.

(c) Assess current test procedures to determine their adequacy in regard to discovering the malfunction which occurred.

TABLE 2-I.- IGS NAVIGATION ERRORS[a]

Parameter	LO+180.078 sec	LO+251.594 sec	LO+299.938 sec	LO+330.766 sec	LO+360.031 sec
V_X (Flt sim), fps	10 555.67	14 934.29	19 667.90	24 693.76	25 294.07
V_X (Corr), fps	10 555.67	14 932.69	19 660.11	24 677.36	25 276.48
ΔV_X (Error), fps	0.00	1.60	7.79	16.40	17.59
ΔV_X (STL), fps	+11.50	17.50	29.00	41.00	43.00
V_Y (Flt sim), fps	-2 965.66	-188.98	1 927.40	3 556.76	4 540.55
V_Y (Corr), fps	-2 965.55	-172.00	1 988.97	3 675.54	4 668.75
ΔV_Y (Error), fps	0.00	-16.98	-61.57	-118.78	-128.20
ΔV_Y (STL), fps	1.00	-14.00	-60.00	-116.40	-124.00
V_Z (Flt sim), fps	-213.83	-224.10	-228.98	-223.32	-215.33
V_Z (Corr), fps	-213.83	-224.07	-228.90	-223.15	-215.15
ΔV_Z (Error), fps	0.00	-0.03	-0.08	-0.17	-0.18
X (Flt sim), ft	764 787	1 664 442	2 491 586	3 168 595	3 909 573
X (Corr), ft	764 787	1 664 430	2 491 355	3 168 003	3 908 471
ΔX (Error), ft	0	12	231	592	1 102
Y (Flt sim), ft	-21 219 044	-21 332 704	-21 291 924	-21 208 274	-21 088 500
Y (Corr), ft	-21 219 044	-21 332 402	-21 289 857	-21 203 526	21 080 024
ΔY (Error), ft	0	-302	-2 067	-4 748	-8 476
Z (Flt sim), ft	-120 867	-136 565	-147 536	-154 565	-160 950
Z (Corr), ft	-120 867	-136 565	-147 533	-154 559	-160 939
ΔZ (Error), ft	0	0	-3	-6	-11

[a]This table is designed to show the effect of the platform gyro (stable element) drift anomaly on IGS navigation and to compare the results following correction with the errors suggested by STL analysis.

Flt sim - Flight reconstruction results.

Corr - Results of flight reconstruction following correction for platform drift.

Error - Flt sim results minus corr. results.

STL - Errors as computed by STL.

TABLE 2-II.- GIMBAL ANGLES AND ATTITUDE ERRORS

Time from lift-off, sec	Pitch, deg			Yaw, deg			Roll, deg		
	θ_b	θ_N	$\Delta\theta_{LV}$	ψ_b	ψ_N	$\Delta\psi_{LV}$	ϕ_b	ϕ_N	$\Delta\phi_{LV}$
-10	89.96	90	0	-0.14	0	-0.15	77.80	77.79	-0.03
-4	89.96	90	0.03	-.14	0	-.14	77.80	77.80	0
3	90.11	90	.13	-.14	0	-.12	78.48	77.80	.68
22	90.07	90	.03	-.43	0	-.43	91.15	90.70	.48
50	70.63	70.49	.14	.07	-0.24	.31	90.76	90.67	.09
75	53.75	53.13	-.05	-.07	-.42	.35	90.50	90.56	-.10
100	39.89	37.79	1.87	-1.69	-.56	-1.18	90.14	90.43	-.35
150	23.54	20.94	2.37	-1.48	-.66	-0.77	88.96	90.25	-1.36
155	21.27	19.76	1.29	-0.04	-.66	.65	87.52	90.24	-2.72
160	20.12	18.58	1.28	-.04	-.67	.69	87.52	90.23	-2.71
168	19.58	(a)	22.69	.04	(a)	-.12	87.52	90.21	-2.69
180	-1.76	(a)	5.45	.47	(a)	.28	87.66	90.21	-2.56
200	-8.21	(a)	-.96	.22	(a)	.11	87.66	90.21	-2.55
250	-7.09	(a)	1.58	.25	(a)	.20	87.41	90.21	-2.80
300	-7.56	(a)	9.36	.22	(a)	.16	86.83	90.21	-3.33
330	-7.60	(a)	12.69	.11	(a)	.14	86.11	90.20	-4.05

Gimbal angles (θ_b, ψ_b, ϕ_b) and attitude errors ($\Delta\theta_{LV}$, $\Delta\psi_{LV}$, $\Delta\phi_{LV}$) were obtained from DAS flight data.

The commanded angles (θ_N, ψ_N, ϕ_N) were obtained as a result of mission reconstruction.

[a]Commanded gimbal angles are not listed at these times since the parameter as computed by the IGS has no meaning with respect to the flight.

TABLE 2-III.- PITCH ATTITUDE ERROR ANALYSIS[a]

Parameter	LO+290.188 seconds		LO+299.938 seconds		LO+330.766 seconds	
	Flight sim. (b)	Corrected (c)	Flight sim. (b)	Corrected (c)	Flight sim. (b)	Corrected (c)
X, ft	2 305 596	2 305 433	2 491 587	2 491 355	3 168 594	3 168 003
Y, ft	-21 308 487	-21 306 962	21 291 923	21 289 857	-21 208 273	21 203 526
Z, ft	-145 308	-145 306	-147 536	-147 533	-154 565	154 558
V_X, fps	18 507.34	18 501.05	19 667.90	19 660.11	24 693.76	24 677.36
V_Y, fps	1 473.73	1 523.36	1 927.40	1 988.97	3 556.76	3 675.54
V_Z, fps	-228.23	-228.16	-228.98	228.90	-223.32	-223.15
R, ft	21 433 351	21 431 817	21 437 718	21 435 639	21 444 223	21 439 441
V, fps	18 567.33	18 565.07	19 763.44	19 761.79	24 949.59	24 950.58
ΔV_E, fps	7 163.11	7 159.12	5 967.38	5 950.46	753.74	748.32
T_G, sec	44.282	44.255	34.456	34.391	3.338	3.316
Q_6 --	0.441249	0.441287	0.451002	0.451192	0.513686	0.515591
V_p, fps	527.24	477.23	373.17	311.12	132.73	12.97
$\bar{B}$, rad	-0.07537	-0.06840	-0.06461	-0.05435	-0.19334	-0.03350
B_{gn}, rad	.12606	.12608	.09517	.09523	.00734	.00736
W_{pr}, rad/sec	.00721	.00482	.01160	.00607	.01160	.00607
B_n, rad	-.12781	-.06163	-.18892	-.07366	-.20483	-.03589
$\Delta\theta_{LV}$ (Recon), deg	6.00	1.642	8.767	2.718	12.615	2.268
$\Delta\theta_{LV}$ (Flight), deg	5.746		9.366		12.690	

[a]Because of the large IGS navigation error during this mission, the suspected gyro drift (see note (c) below) was removed from the accelerometer and gimbal angle data and the mission was then reconstructed. The inflight pitch attitude error ($\Delta\theta_{LV}$) may thus be compared with the reconstructed and the corrected errors in order to evaluate the effects of the IMU anomaly on the GDC output.

[b]Flight sim data obtained from FORTRAN reconstruction.

[c]These results were obtained by removing the following platform drift error: pitch down 33.4 deg/hr between LO+195 and LO+243 seconds; pitch down of LO+10 deg/hr between LO+243 seconds and SECO.

TABLE 2-IV.- POSITION AND VELOCITY COMPARISON

Condition	Source of data	Position, ft			Velocity, fps		
		X	Y	Z	V_X	V_Y	V_Z
Prior to platform release	Flight	-17 328	-20 909 920	-56 184	1 282.36	0	-395.46
	FORTRAN	-17 325	-20 909 916	-56 178	1 282.36	0	-395.46
	Op. Prog.	-17 324	-20 909 917	-56 184	1 282.38	0	-395.39
After platform release	Flight	-15 396	-20 909 920	-56 780	1 282.34	-0.02	-394.92
	FORTRAN	-15 393	-20 909 916	-56 772	1 282.44	.11	-394.94
	Op. Prog.	-15 393	-20 909 917	-56 780	1 282.45	.12	-394.91
After lift-off (LO+2.438 sec)	Flight	-9 116	-20 909 948	-58 712	1 282.33	-24.15	-394.58
	FORTRAN	-9 113	-20 909 945	-58 707	1 282.42	-23.98	-394.60
	Op. Prog.	-9 116	-20 909 948	-48 714	1 282.44	-23.98	-394.57
Before update (LO+102.984 sec)	Flight	183 912	-20 997 052	-98 720	3 826.15	-1 968.82	-360.00
	FORTRAN	183 968	-20 997 049	-98 716	3 826.18	-1 968.67	-360.05
	Op. Prog.	183 967	20 997 064	-98 714	3 826.31	-1 968.49	-359.88
Between updates (LO+127.156 sec)	Flight	299 908	-21 052 568	-108 248	5 956.34	-2 621.21	-311.27
	FORTRAN	299 949	-21 052 546	-108 254	5 956.33	-2 621.31	-311.41
	Op. Prog.	299 961	-21 052 559	-108 226	5 956.52	-2 621.09	-311.05
Following updates (LO+148.922 sec)	Flight	458 544	-21 117 148	-114 200	8 805.00	-3 353.03	-230.81
	FORTRAN	458 574	-21 117 106	-114 188	8 805.01	-3 353.29	-230.83
	Op. Prog.	458 587	-21 117 115	-114 162	8 805.17	-3 353.03	-230.51
After lift-off (LO+201.438 sec)	Flight	1 001 920	-21 273 868	-125 500	11 668.31	-2 148.72	-218.79
	FORTRAN	1 001 916	-21 273 798	-125 500	11 668.18	-2 148.81	-218.92
	Op. Prog.	1 001 938	-21 273 801	-125 449	11 668.33	-2 148.60	-218.57
Prior to SECO (LO+330.766 sec)	Flight	3 168 636	-21 308 344	-154 552	24 693.99	3 557.03	-223.14
	FORTRAN	3 168 594	-21 208 273	-154 565	24 693.76	3 556.76	-223.32
	Op. Prog.	3 168 623	-21 208 274	-154 477	24 693.72	3 556.98	-222.97
After SECO (LO+333.625 sec)	Flight	3 240 144	-21 197 924	-155 188	25 327.23	3 730.73	-220.82
	FORTRAN	3 240 108	-21 197 855	-155 200	25 326.97	3 730.47	-221.01
	Op. Prog.	3 240 136	-21 197 857	-155 110	25 326.95	3 730.68	-220.65
At SECO+20 (LO+355.203 sec)	Flight	3 787 219	-21 110 180	-159 892	25 318.45	4 394.75	-216.13
	FORTRAN	3 787 394	-21 110 071	-159 909	25 318.12	4 394.84	-216.25
	Op. Prog.	3 787 419	-21 110 075	-159 810	25 318.12	4 395.07	-215.87
At SECO+25 (LO+360.031 sec)	Flight	3 909 648	-21 088 568	-160 936	25 294.34	4 540.76	-215.21
	FORTRAN	3 909 573	-21 088 500	-160 950	25 294.07	4 540.55	-215.32
	Op. Prog.	3 909 599	-21 088 503	-160 850	25 294.08	4 540.78	-214.94

Flight - DAS flight data

FORTRAN - FORTRAN flight reconstruction results

Op. Prog. - Operational Program flight reconstruction results

TABLE 2-V.- PLATFORM AZIMUTH MISALINEMENT[a]

Time period	FORTRAN results, radians	Operational Program results, radians
Platform release	0.0001347	0.0001759
104 sec update	- .0091635	- .0092567
144 sec update	- .0091106	- .0091511

[a]STL analysis indicated platform azimuth misalinement to be approximately -0.52°.

Values of V_{ZG} received by the IGS via DCS from the Burroughs system were -348.5 fps at 105 seconds and -199.0 fps at 145 seconds.

Differences between the final FORTRAN and Operational Program results above amounts to approximately 9 arc seconds or equivalently a 1 fps out-of-plane velocity error at SECO.

TABLE 2-VI.- IGS INJECTION CONDITIONS

[At approximately SECO + 20: LO+355.203 sec]

Parameter	IGS flight values (a)	Op. Program reconstruction (c)	IGS data corrected for gyro drift (d)	Quoted insertion condition (e)
V_X, fps	25 318.45	25 318.12	25 300.54	
V_Y, fps	4 394.75	4 395.07	4 522.93	
V_Z, fps	-216.13	-215.87	216.07	
X, ft	3 787 219	3 787 419	3 786 376	
Y, ft	-21 110 180	21 110 075	-21 102 213	
Z, ft	-159 892	159 810	159 898	
V, fps	25 697.95	25 697.65	25 702.55	25 682
R, ft	21 447 804	21 447 722	21 439 813	21 439 841
V_R, fps	146.73	146.62	18.10	6.72
V_I, fps	[b]2.66	2.66	2.97	-
Γ, deg	0.3273	0.3089	0.0573	0.015

[a]IGS parameters listed were obtained from inflight DAS data.

[b]Out-of-plane velocity was obtained from Op. Program reconstruction.

[c]Op. Program results were derived from reconstruction of the mission using DAS gimbal angle and accelerometer data.

[d]This data was derived by reconstructing the flight and removing the gyro drift error. It was assumed a pitch-down drift of 33.4 deg/hr occurred between 195 and 243 seconds and a drift of 10 deg/hr occurred from 243 seconds through the end of flight.

[e]Quoted values are based on values obtained from NASA on April 7, 1965.

TABLE 2-VII.- IVAR OPERATIONS[a]

[IVI and FDI Readings]

Time from lift-off, sec	IVI readings, fps			Spacecraft attitude errors, deg		
	IVI-X	IVI-Y	IVI-Z	Pitch	Yaw	Roll
354	-16.7	-1.7	-3.3	-173	-12	85
356	-16.9	-1.6	-3.3	-174	-12	86
358	-17.8	-1.4	-3.7	-174	-11	86
360	-19.3	-1.3	-3.6	-175	-11	86
362	-21.8	-1.9	0.5	175	-21	67
364	-22.8	3.0	1.6	172	-19	37
366	-24.3	2.7	1.3	175	-16	11
368	-26.2	2.7	-1.36	-175	-14	-14
370	-27.4	1.1	-2.0	-175	-15	-21
372	-28.9	3.9	-2.7	-174	-15	-3

[a]FORTRAN reconstruction results presented. Operational Program results are practically identical to the above. See discussion in section 2.3.6.

Convention:

IVI-X	IVI-Y	IVI-Z
+forward	+right	+up
-aft	-left	-down

TABLE 2-VIII.- IGS DISCRETE EVENTS

Time from lift-off, sec (a)	Event	Comments
-3.76/-3.32	Platform release	Based on reconstruction of the IGS position and velocity data in the time period prior to platform release through lift-off.
0	Lift-off	Table 2-IX will indicate that the IGS lift-off sync was late by approximately 2 msec.
10.180	Roll program initiate	Corrected based on data listed in reference 4.
20.436	Roll program termination	Corrected based on data listed in reference 4.
22.972	Start pitch step I	Corrected based on data listed in reference 4.
88.448	Start pitch step 2	Corrected based on data listed in reference 4.
105.200	Gain change	Corrected based on data listed in reference 4.
105.391	Receipt of first update (value - 348.5 fps)	Time quoted is DAS time in mode when update is seen on telemetry.
119.290	Start pitch step 3	Corrected based on data listed in reference 4.
146.516	Receipt of second update (value - 199.0 fps)	Time quoted is DAS time in mode when update is seen on telemetry.
167.986	Time stage II guidance initiate	Time quoted is the time at which attitude error signals, generated by the IGS stage II equations, are first sent to the autopilot.
333.628	IGS SECO (uncertainty ± 7.6 msec)	Time quoted is based on the GDC clock reading just after the SECO discrete is issued. It is assumed that the IGS clock is perfectly sychronized with lift-off.
354.503	IVAR initiation	Time is again quoted to reflect the time at which IVAR attitude errors are first displayed.

[a] All times are quoted based on GDC clock readings. The times are not corrected for lift-off sync errors.

TABLE 2-IX.- LIFT-OFF SYNCHRONIZATION WORK SHEET

Range time, G.m.t., sec	IGS time in mode (a)	Flow tag	Frame sync initiation time (b)	IGS frame sync recognition (c)	Difference (d)
51 849.625	9.7656	114 036	9.879	9.8746	-0.004
51 852.025	12.0781	54 001	12.279	12,2941	.015
51 861.624	21.7812	114 036	21.878	21.8902	.012
51 868.823	28.8594	54 001	29.077	29.0754	- .002
51 871.223	31.2500	54 001	31.477	31.4660	[e]- .011
51 873.623	33.6563	54 001	33.877	33.8723	- .005
51 876.022	36.0625	54 001	36.276	36.2785	.003
51 981.611	141.6563	54 001	141.865	141.8723	.007
51 984.011	144.0781	54 001	144.265	144.2941	.029
51 986.411	146.5156	114 122	146.665	146.6756	.010
51 988.811	148.9219	114 122	149.065	149.0819	.017
51 991.210	151.3438	114 036	151.464	151.4528	[e]- .011
51 993.613	153.7656	114 036	153.867	153.8746	.008
51 996.010	156.1406	114 036	156.264	156.2496	[e]- .014
51 998.410	158.5469	114 036	158.664	158.6559	[e]- .009
52 000.809	160.9531	114 036	161.063	161.0621	- .001
52 003.209	163.3438	114 122	163.463	163.5038	[f].041
52 005.609	165.7189	114 122	165.863	165.8789	.016
52 010.408	170.4531	54 001	170.662	170.6691	.007
52 012.808	172.8593	54 001	173.062	173.0753	.013
52 015.208	175.2656	54 001	175.462	175.4816	.019
52 017.608	177.6719	54 001	177.862	177.8879	.026
52 022.407	182.5469	114 036	182.661	182.6559	.005
52 051.204	211.2813	54 001	211.458	211.4973	.039
52 053.604	213.7500	114 036	213.858	213.8590	.001
52 080.002	240.0625	54 001	240.256	240.2785	.023
52 082.401	242.5156	114 122	242.655	242.6756	.021
52 084.801	244.9844	114 036	245.055	245.0934	.033
52 111.199	271.2812	114 122	271.453	271.4412	[e]- .012
52 113.598	273.7500	114 036	273.852	273.8590	.007
52 156.794	316.8906	114 122	317.048	317.0506	.003
52 175.993	336.1406	114 036	336.247	336.2496	.003
52 183.192	343.2969	114 122	343.446	343.4569	.011
52 190.391	350.4531	54 001	350.645	350.6691	.024
52 192.791	352.9688	114 036	353.045	353.0778	.033
52 204.790	364.8750	54 001	365.044	365.0910	[f].047

[a]IGS time in mode - IGS computed elapsed time from lift-off, quantized to 2^{-6} second (15.6 msec).

[b]Frame sync initiation time - Elapsed time from launch when frame sync was initiated. Computed in the following manner:

Range time (from table)
-Lift-off time (51 840.064 seconds)
+Delay between range time and frame sync (318 msec)

Total =Frame sync initiation time

TABLE 2-IX.- LIFT-OFF SYNCHRONIZATION WORK SHEET - Concluded

[c]IGS frame sync recognition - IGS time at which frame sync was recognized in the GDC. Computed by adding the Δt (from the clock in IGS executor to the frame sync test in the I/O which recognized the frame sync discrete) to IGS time in mode. The following corrections were thus added to IGS time in mode:

Flow tag	t (msec)
114 036	109
114 122	160
54 001	216

[d]The difference represents the apparent lift-off synchronization error and is obtained by subtracting IGS frame sync recognition from the frame sync initiation time. To use this data properly, it must be understood that:

a. IGS time is quantized to 15.6 msec.

b. The DAS frame sync discrete is tested by the IGS at approximately 50 msec intervals.

c. The frame sync request remains on for a maximum of 75 msec or until it is recognized by the IGS.

Thus the negative numbers in the sixth column are most representative of frame sync accuracy. The negative sign implies the IGS was late in recognizing lift-off. The largest negative number represents a situation where the IGS recognized the frame sync discrete as soon as it comes up and the IGS time in that same frame possessed the largest possible quantization error (15.6 msec). Assiming both these conditions occurred at 156 seconds following lift-off, we arrive at the conclusion that the IGS was approximately 2 msec late in lift-off time determination.

[e,f]The difference between the largest negative and the largest positive values should be approximately 65 msec. The largest negative number, of course, represents the situation explained above. The largest positive number would imply that the DAS sync request was initiated just after the IGS completed its test on the discrete and a full 50 msec had to elapse before it was recognized. Similarly the large positive number would suggest that no quantization error occurred in the telemetered quantity - IGS time in mode.

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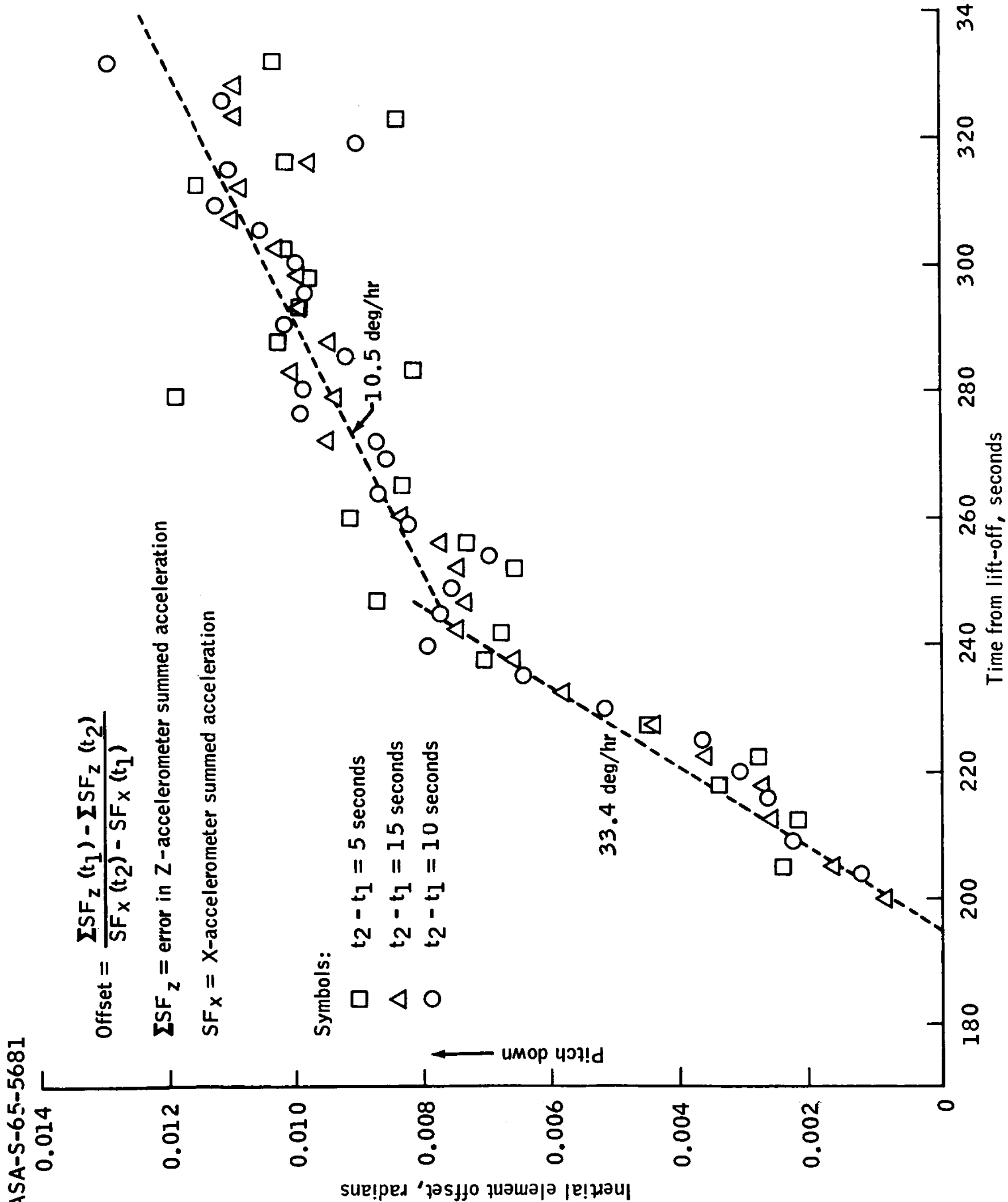

Figure 2-1. - Platform inertial element offset

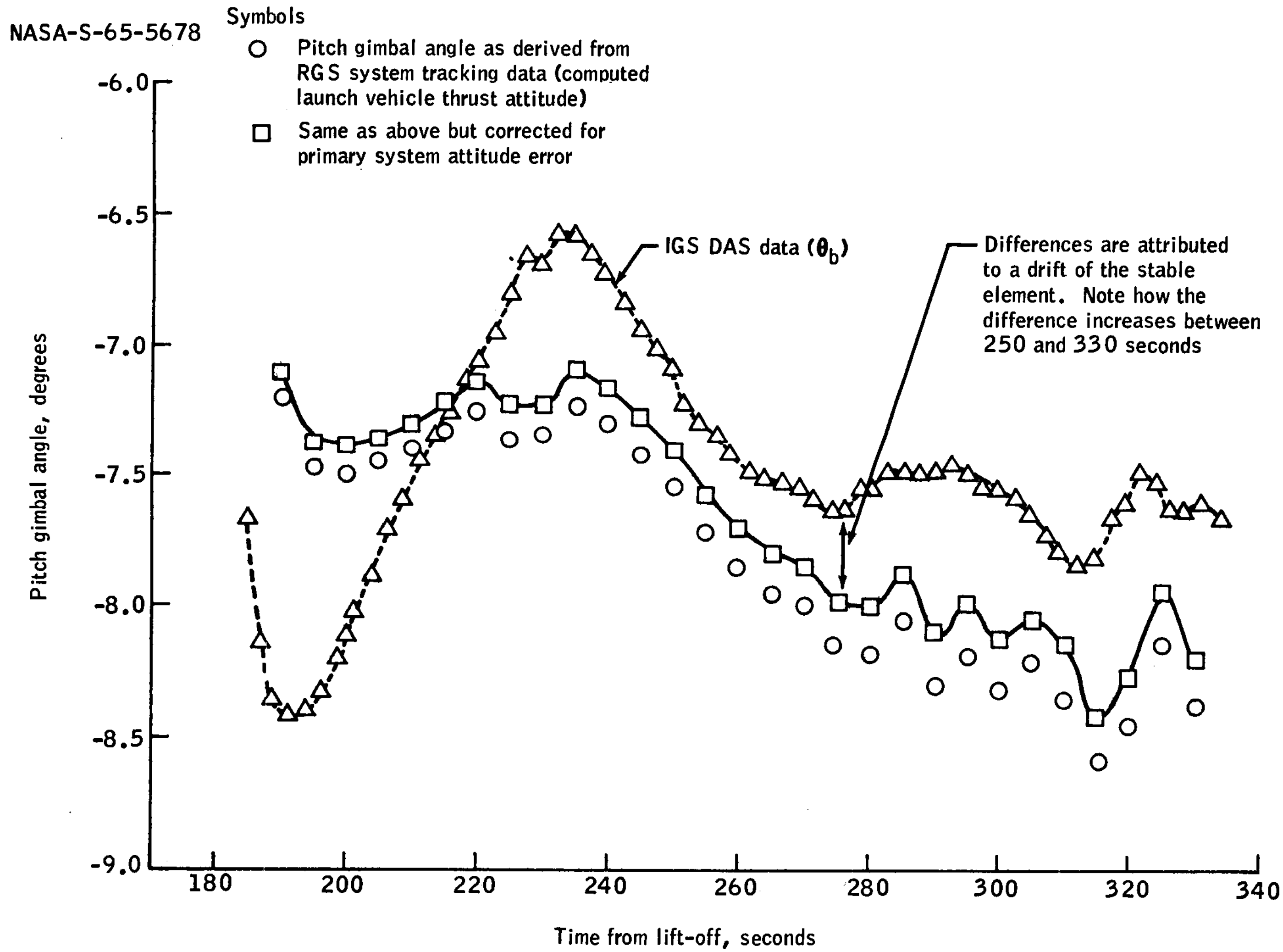

Figure 2-2. - Comparison of RGS and IGS inertial attitude

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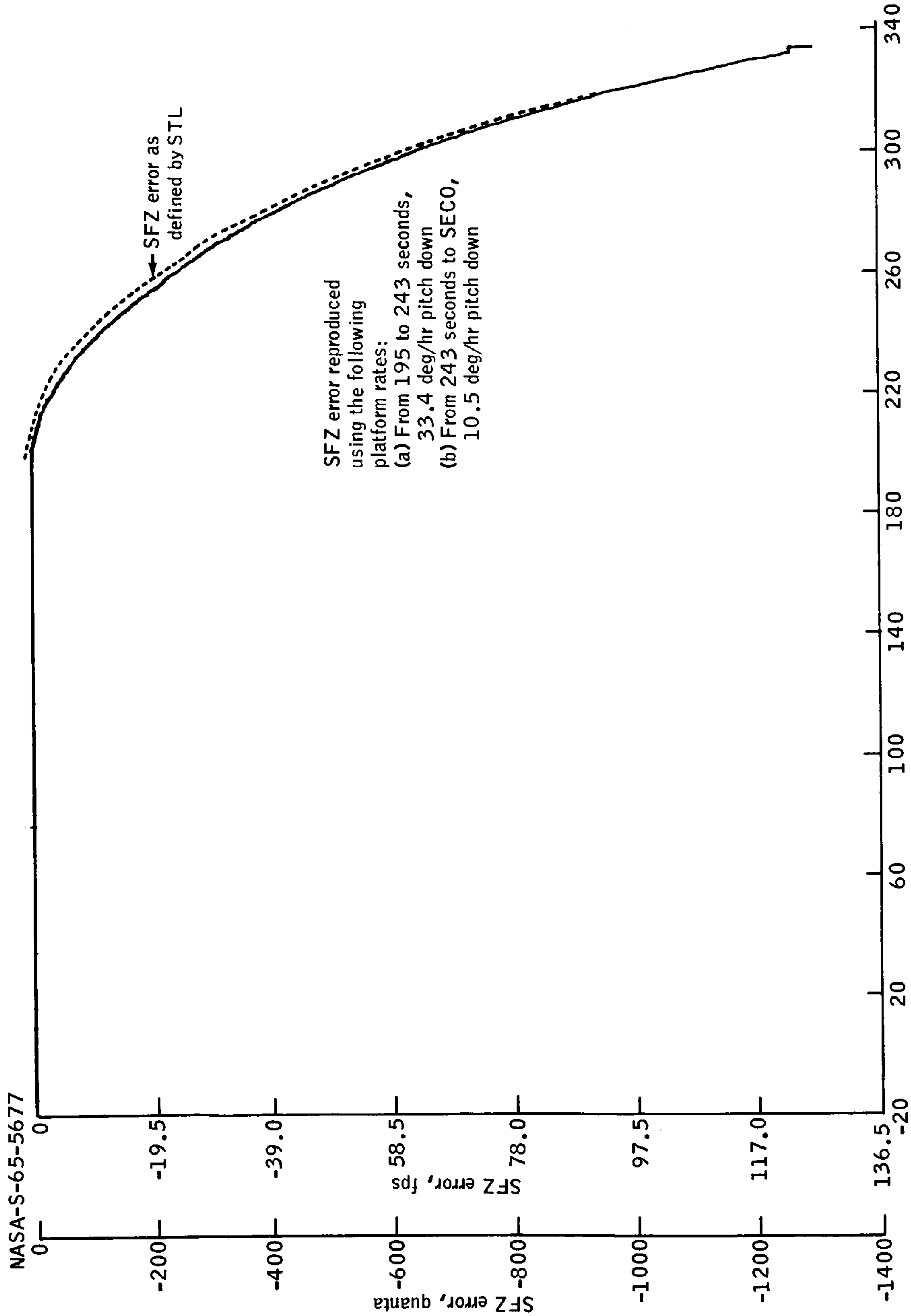

Figure 2-3.- Error characteristic of Z-accelerometer based on FORTRAN IGS data.

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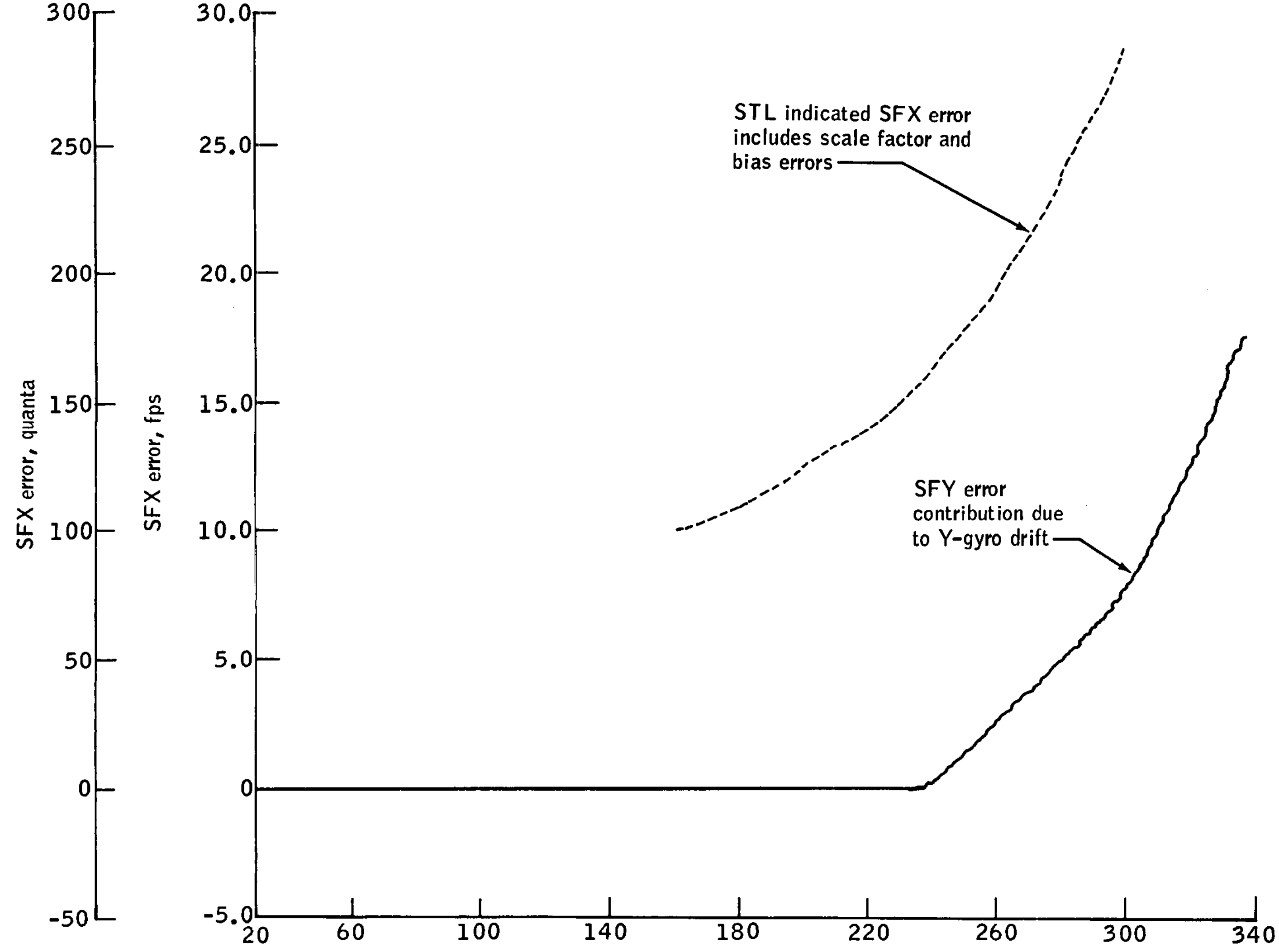

Figure 2-4.- Error characteristic of X-accelerometer based on FORTRAN IGS data.

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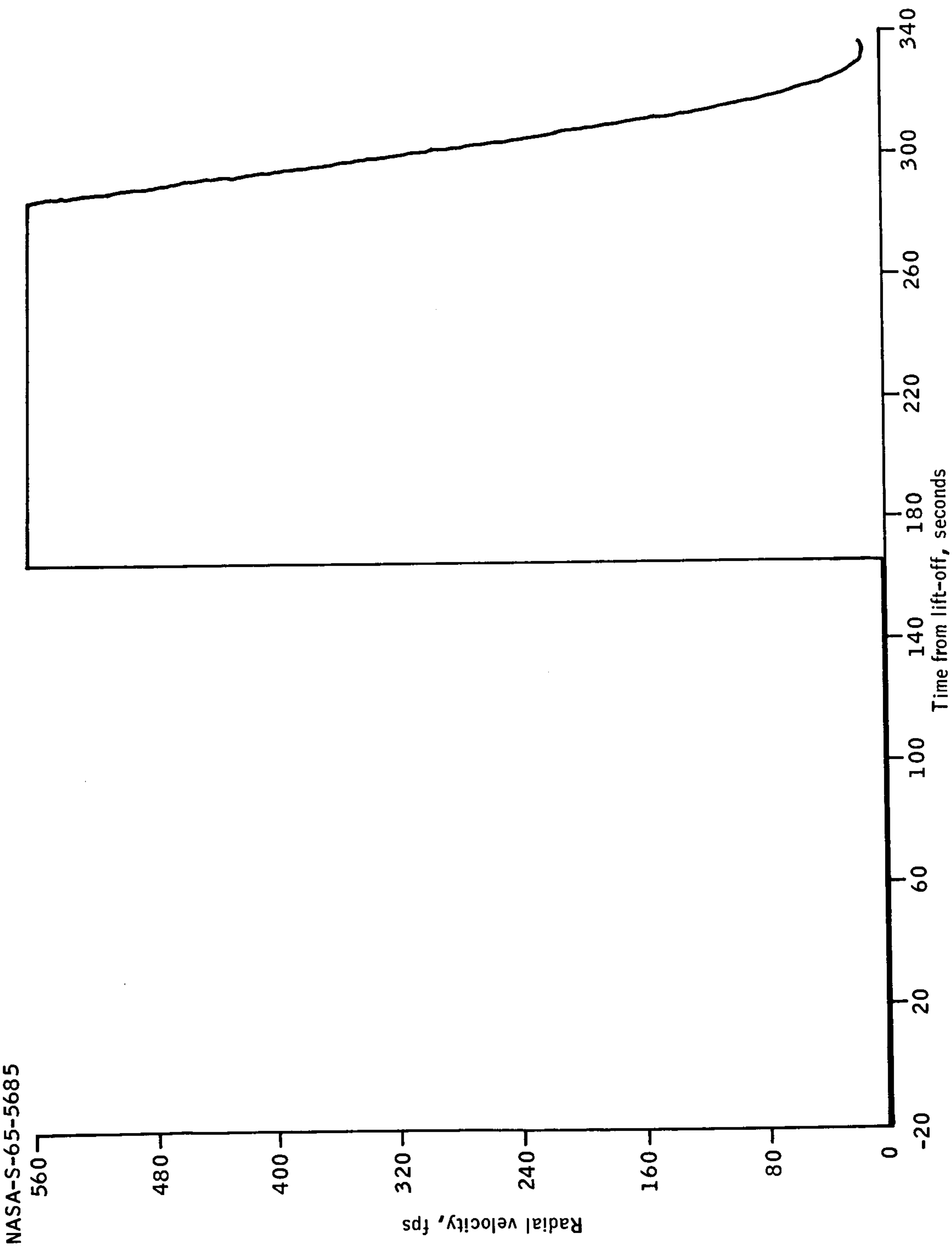

Figure 2-5.- Radial velocity based on FORTRAN IGS data.

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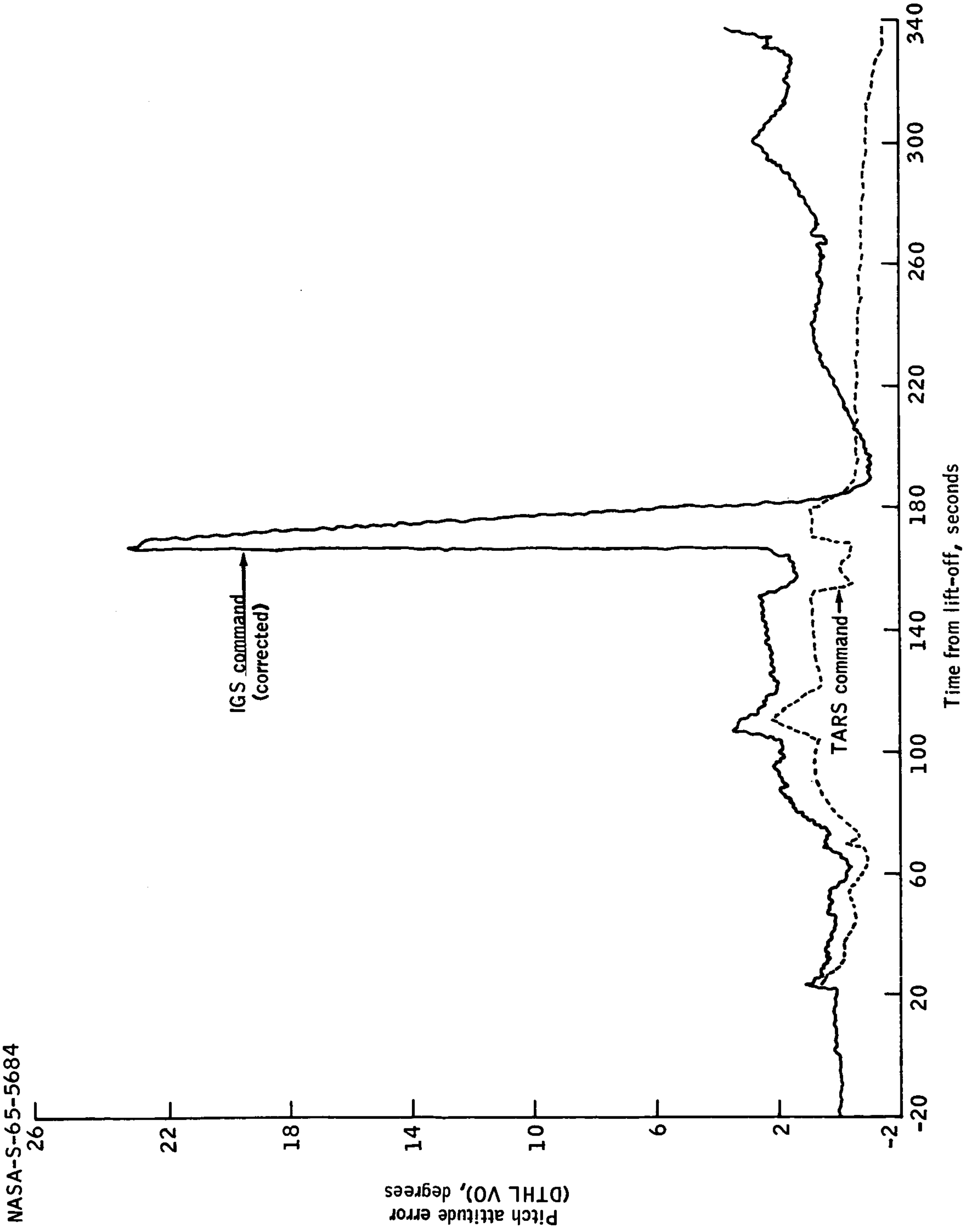

Figure 2-6.- Pitch command based on FORTRAN IGS data.

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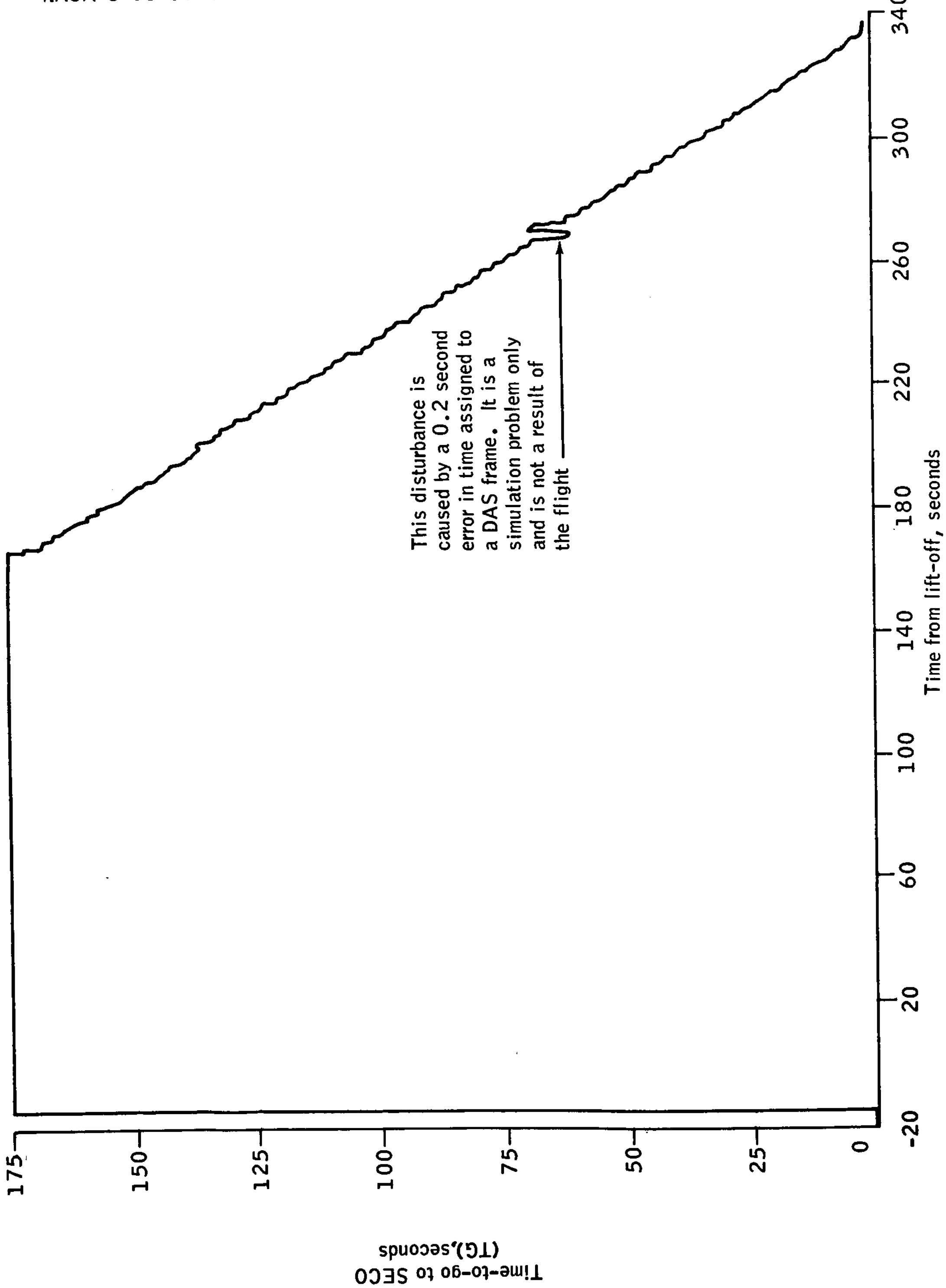

(a) FORTRAN IGS data

Figure 2-7.- Time-to-go to SECO.

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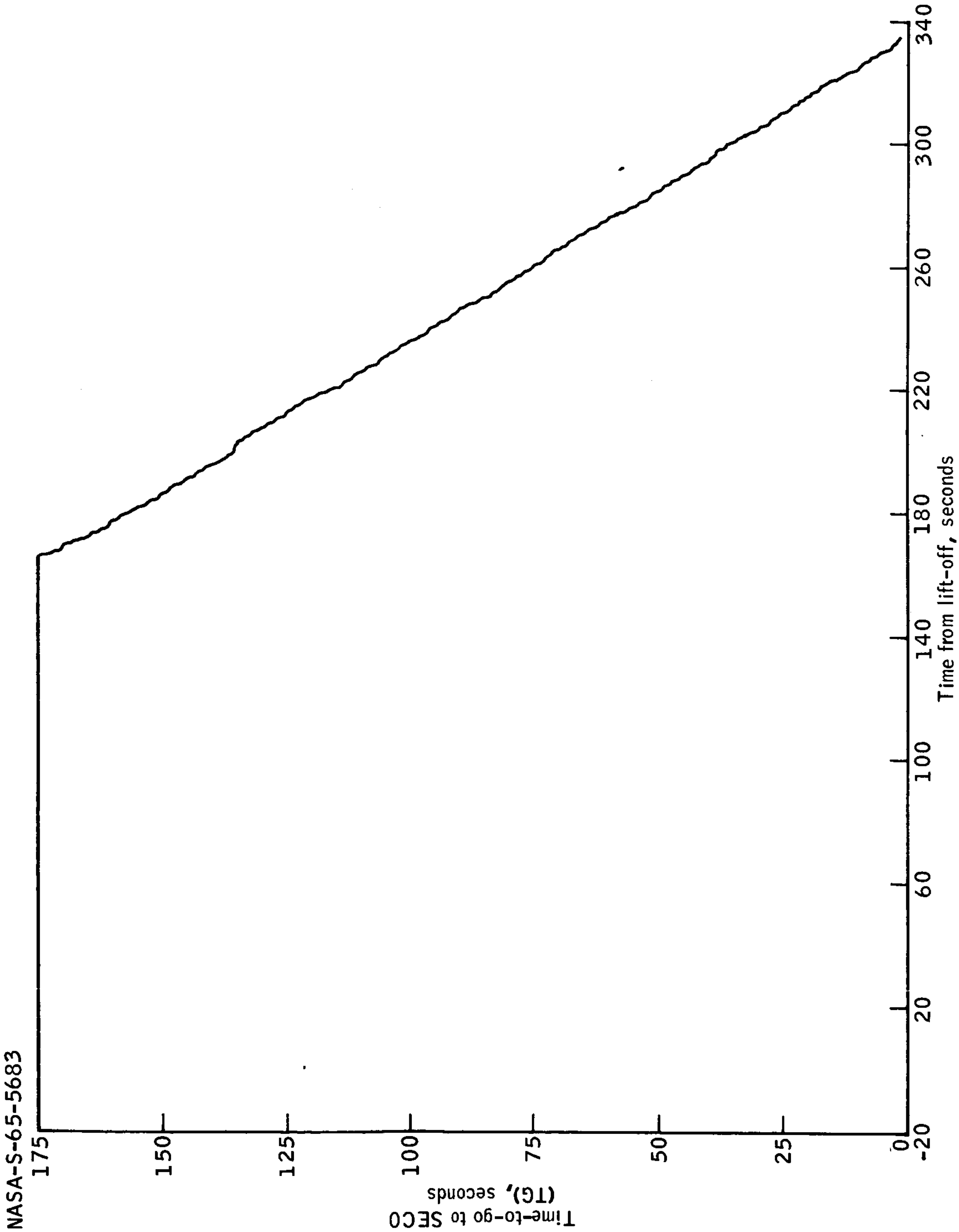
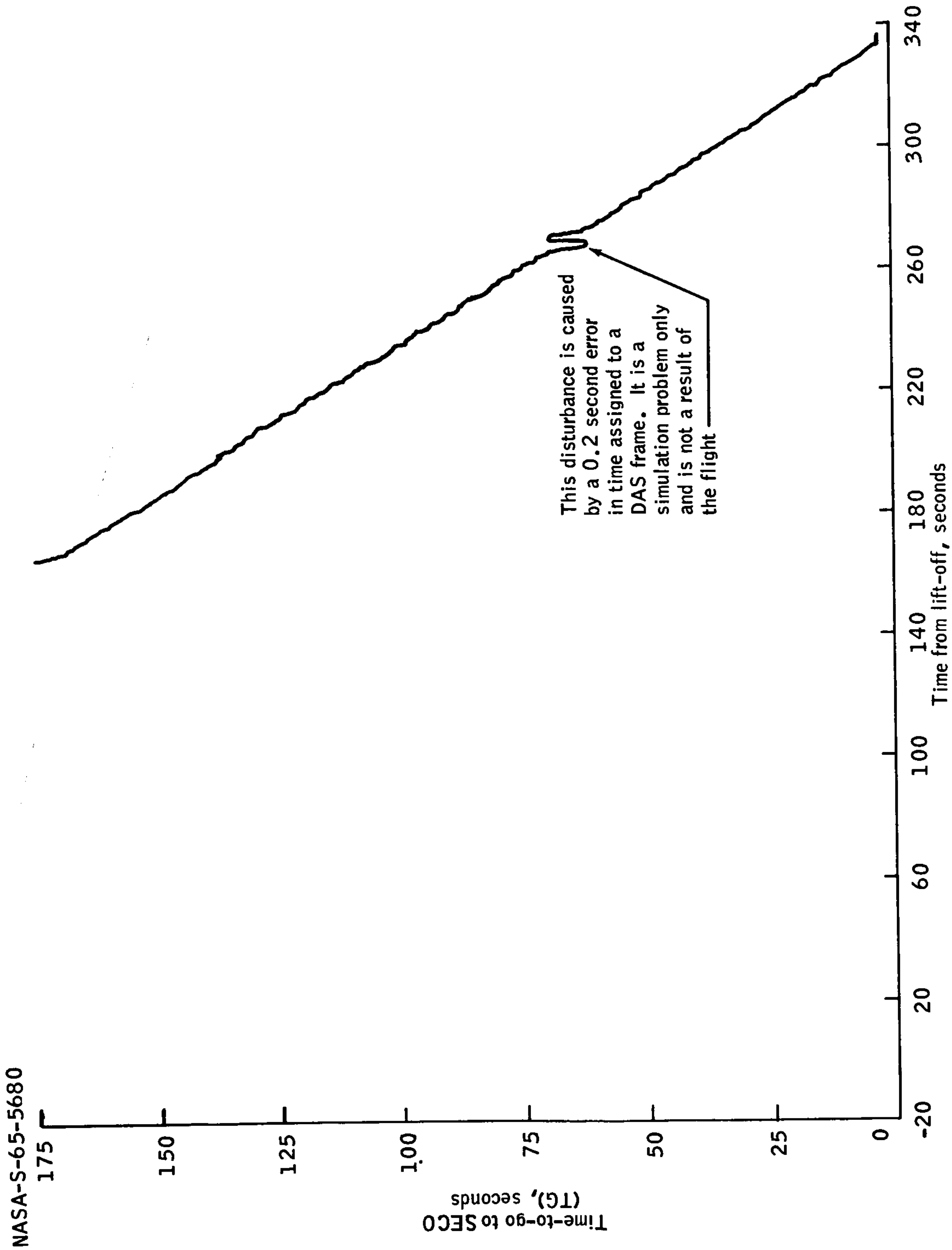


(b) GT-3 flight data

Figure 2-7.- Time-to-go to SECO.



(c) Operational Program

Figure 2-7.- Time-to-go to SECO.

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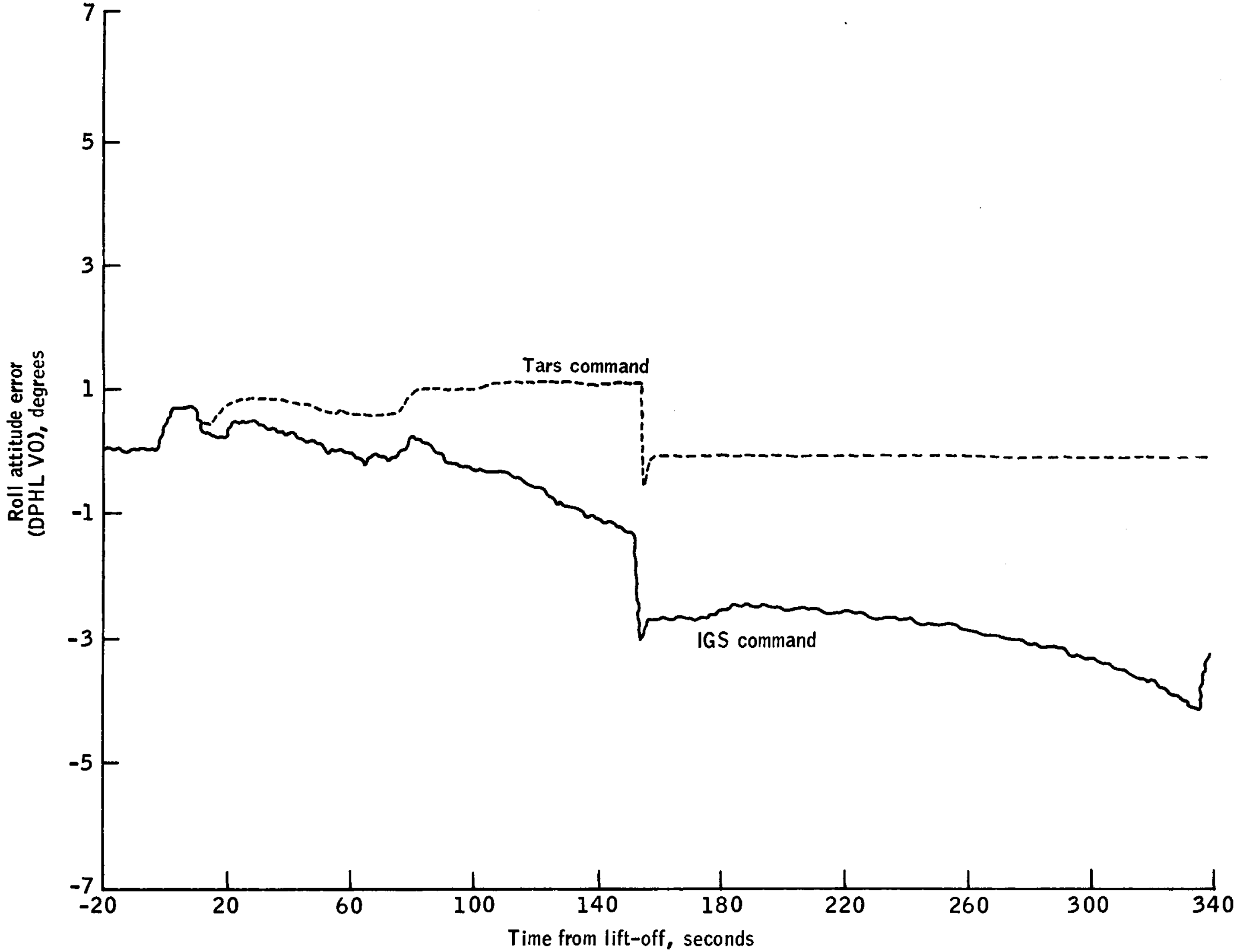

Figure 2-8.- Roll command based on GT-3 flight data.

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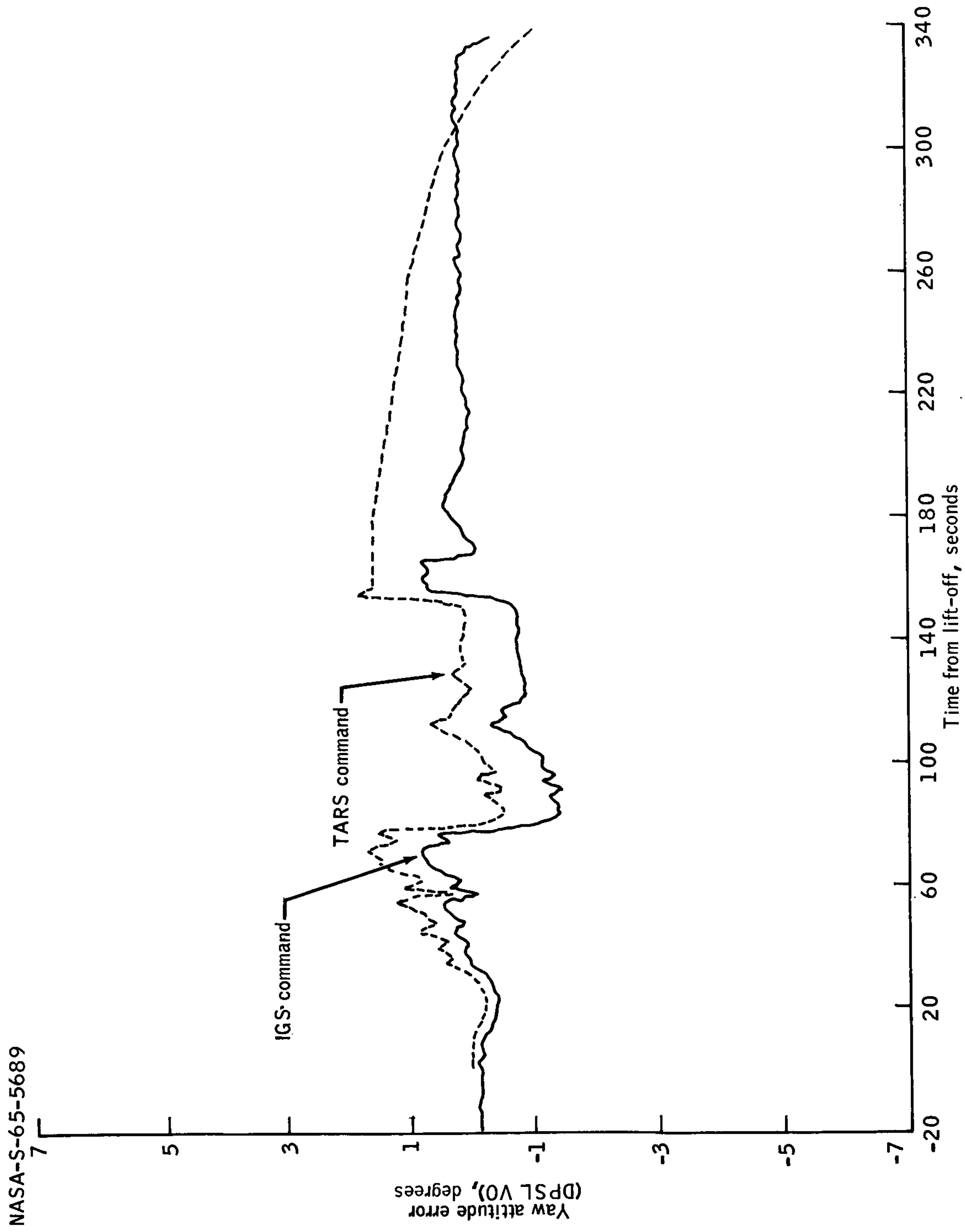

(a) GT-3 flight data

Figure 2-9. - Yaw command

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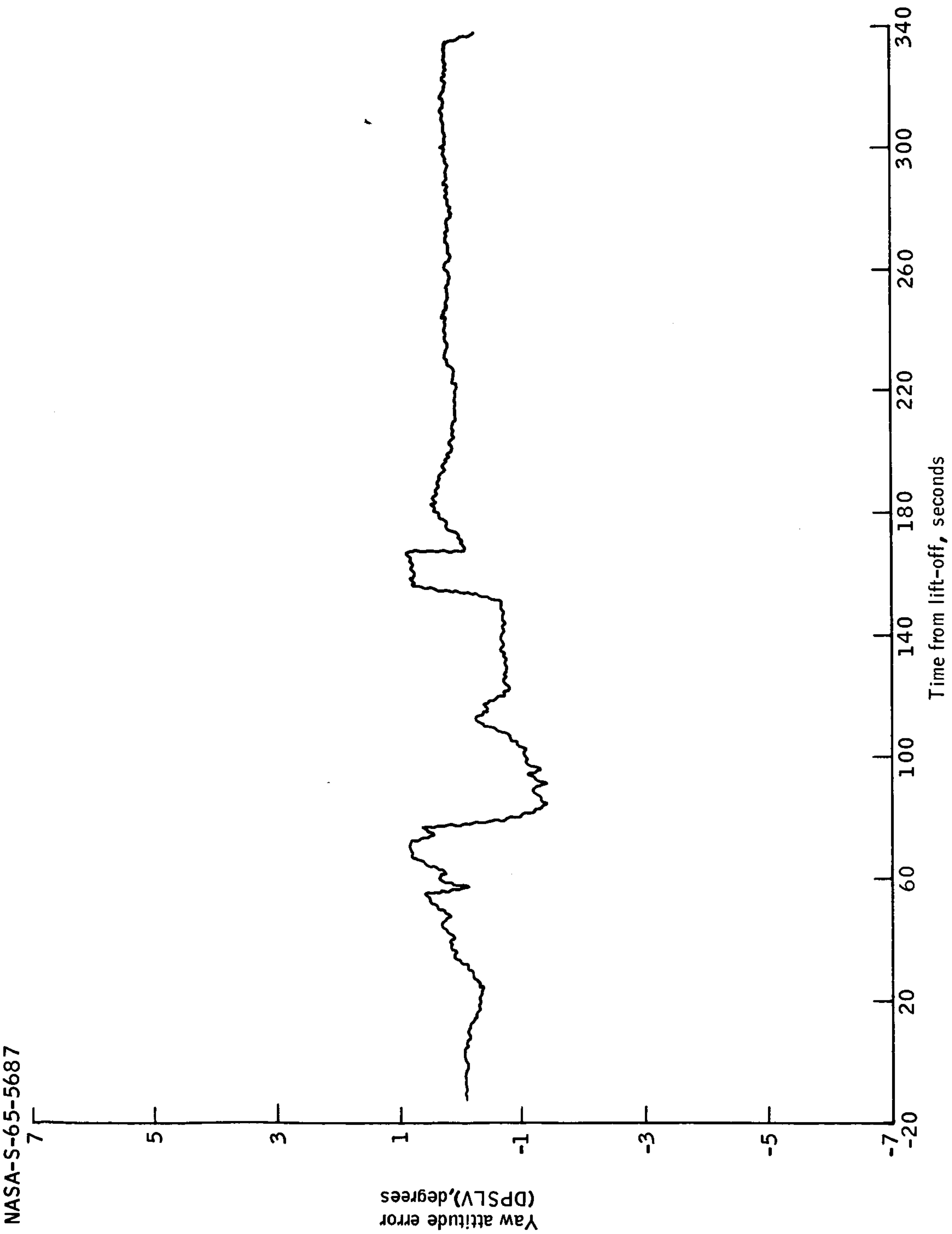

(b) Operational Program

Figure 2-9. - Yaw command

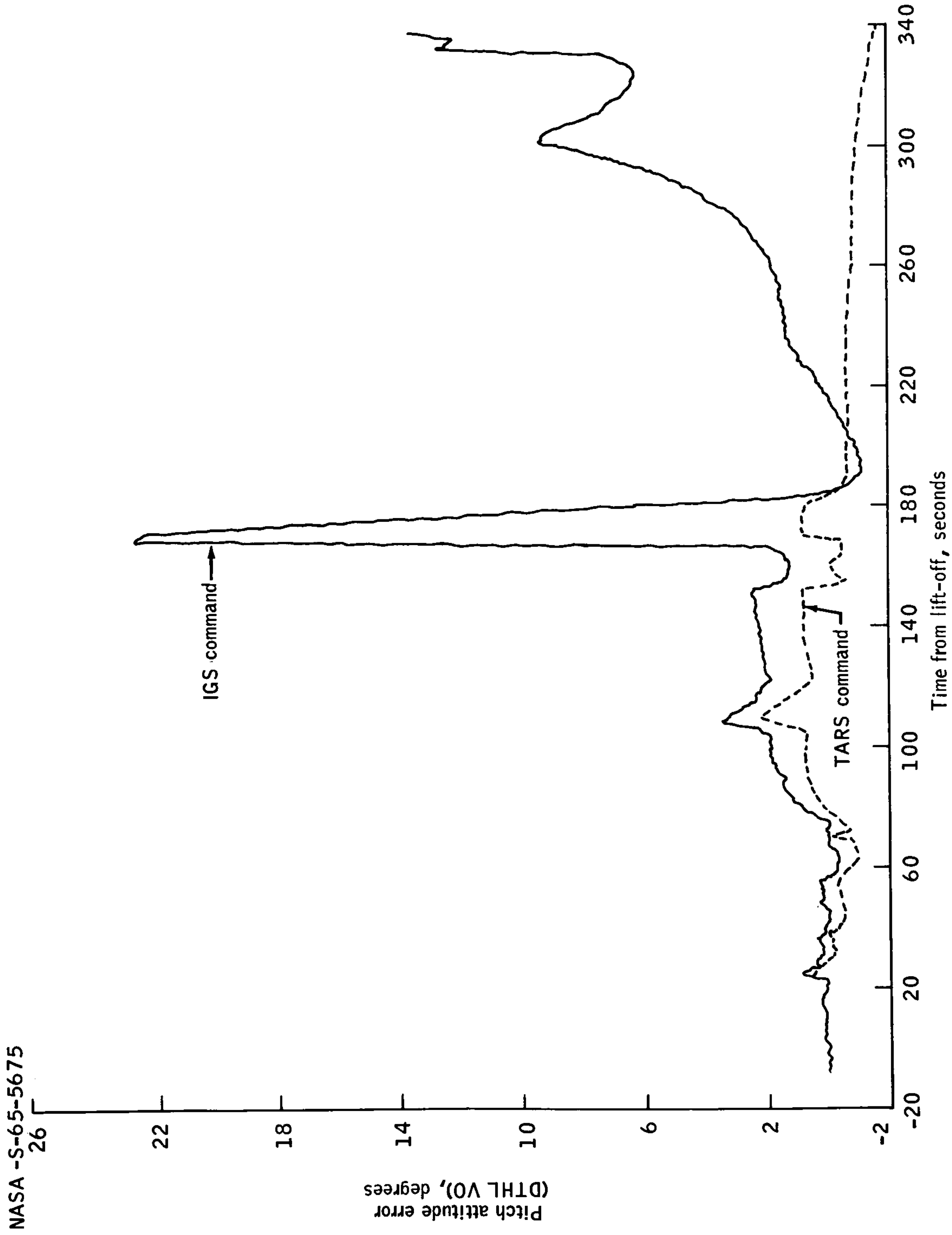

Figure 2-10.- Pitch command based on GT-3 flight data.

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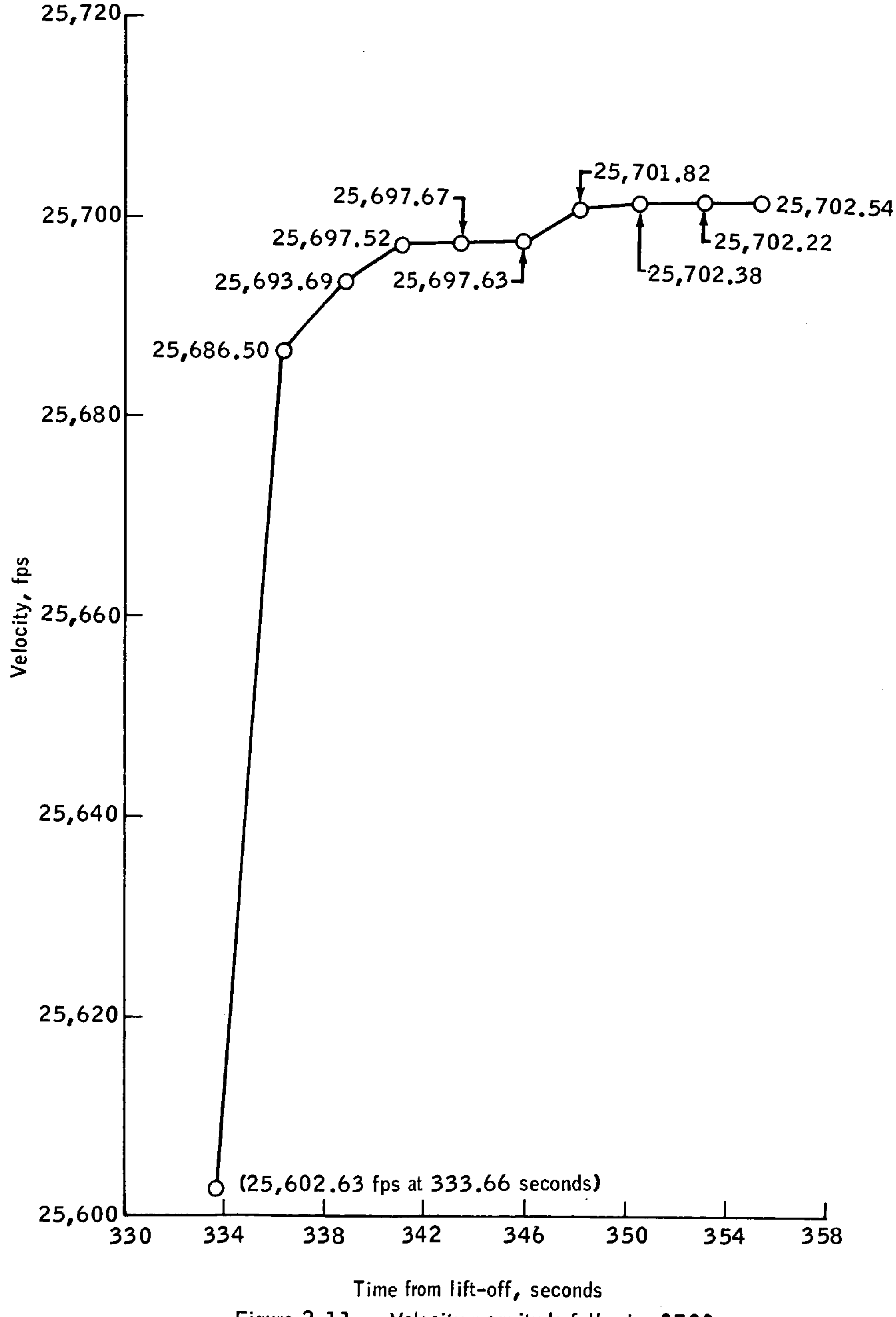

Figure 2-11. - Velocity magnitude following SECO

3.0 GT-3 REENTRY POSTFLIGHT ANALYSIS

This section presents the results of the reconstructed operation of the spacecraft onboard computer during the reentry phase of the GT-3 flight. The purpose of the reconstruction was to verify that no anomalies occurred in the computer during the reentry portion of the mission.

The study was made using the Operational Program simulation, which executes a Gemini program on the 7090 DPS in fixed point arithmetic and 26-bit word length. The accelerometer outputs from the flight telemetry data were used as inputs to the program. The DCS quantities used in the reconstruction are given for reference in table 3-I.

3.1 Summary of Results

Table 3-II contains a comparison of the reconstructed data and the telemetry data at the end of retro, at a navigated altitude of 400 000 ft at initiation of guidance, and at a point beyond the cut-off of guidance. The differences are considered to be negligible for the purposes of the reconstruction, and the reasons for the differences are explained in paragraph 3.3.

Of more significance than the individual differences are the total dispersions in position and velocity defined as follows:

(a) Position error - Given differences in radius, latitude, and longitude (δ_r, $\delta\phi$, and $\delta\theta$, respectively), the total position error (ε_p) in feet is defined by the relation

$$\varepsilon_p^2 = (\delta r)^2 + (60 \times 6076 \times \delta\phi)^2 + (60 \times 6076 \times \cos\phi\ \delta\theta)^2$$

The position error at time-in-mode 1372.875 seconds, for example, is 611 ft.

(b) Velocity error - Given differences in velocity, flight-path angle, and heading (δV_E, $\delta\gamma$, and $\delta\psi_E$, respectively), the total velocity error (ε_V) in feet per second is defined by the relation

$$\varepsilon V^2 = (\delta V_E)^2 + \left(V_E\ \frac{\delta\gamma}{57.3}\right)^2 + \left(V_E \cos\gamma\ \frac{\delta\psi_E}{57.3}\right)^2$$

The velocity error at time 1372.875 seconds is found to be 0.438 fps.

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For the purposes of the reconstruction, retrofire time can be estimated with extremely good accuracy as follows. There is a frame of telemetry data for which the time-in-mode is 571.531 seconds. Examination of the platform readings SF_X, SF_Y, and SF_Z for this frame show that retrofire most probably did not occur prior to the reading of the accelerometers. Furthermore, the flow tag corresponding to this telemetry frame shows that the program was executing preliminary navigation equations prior to calculating gravitational acceleration. Therefore, the time-to-go-to-retrofire (T_R) discrete must have gone negative somewhere between the reading of the clock at 571.531 seconds, and the sensing of the T_R discrete. Use of this assumed retrofire time has allowed equavalent to a time error of 15 msec, which is the maximum obtainable accuracy due to DAS time resolution.

An attempt was made to use the above information to obtain the range time at which retrofire occurred with the same accuracy. The range time recorded in the telemetry frame under discussion was 16 405.00 seconds, and this number should represent range time of retrofire with very little error. However, there is an anomaly in the range time which destroys confidence that retrofire did occur at 16 405.00 seconds. This anomaly can be seen as follows:

The first reentry telemetry frame contains a time-in-mode of 0.884 second and a range time of 15 831.62 seconds (04:23:51.62 g.e.t.). The elapsed time-in-mode between this frame and retrofire is 571.531 - 0.844 = 570.687 seconds. The range time of retrofire then should be approximately 15 831.62 + 570.69 = 16 402.31 seconds (04:33:22.31 g.e.t.) and not 16 406.00 seconds (04:33:25 g.e.t.) as indicated by the telemetry. Since this discrepancy exists, it has not been found possible to use time-in-mode of retrofire to establish range time of retrofire with confidence.

3.2 Description of the Program

Figure 3-1 is a block diagram of the program used in the reconstruction of the GT-3 reentry. The functions performed by the program are as follows:

(a) Raw data - The source of this data is a tape, obtained from NASA, containing the onboard recorder telemetry data. The quantities needed for reconstruction, namely; t, SF_X, SF_Y, SF_Z, ϕ_b and flow tag, were converted to cards to be used as inputs for the data generator program.

(b) Data generator program - This program reads data cards, and breaks each DAS frame up into a reasonable number of computation cycles,

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depending on what portion of the math flow is being used. Corresponding to each computation cycle time generated, linear interpolation is used on the accelerometer outputs to apportion pulses over the same computation cycle times. Thus for each pass through the operational program, the data generator provides Δt_c, F_X', F_Y', F_Z' as inputs.

In addition, the data generator calls a subroutine, below 400 000 ft, to provide roll gimbal angle as a function of time. The first pass through this subroutine reads time and roll angle from the telemetry tape, adjusts the time associated with the roll angle by means of the flow tag, and stores the angle as a function of time in the form of a table. In succeeding passes, a table look-up routine is used to calculate roll gimbal angle for input to the operational program.

(c) Main program - This program acts as an executor program calling subroutines to compute the inputs which are required for the operational program each computation cycle. In addition, this program writes the output tape containing the reconstructed flight data.

(d) Control program - This program acts as a communications interface between the operational program and the main program. It selects the required inputs obtained by the main program out of common locations and passes them on to the simulator as requested. It also obtains information to be printed from the simulator and places it in common locations to be used by the main program each computation cycle.

(e) Gemini Operational Program simulator (OPS) - This program simulates the instruction code, scaling, fixed point arithmetic, and 26-bit word length of the actual Gemini computer. In addition, all the subroutines used by the OPS program are identical to those used by the real GDC. It accepts platform inputs, roll gimbal angle, and computation cycle length from the control program, and generates the reconstructed telemetry data each computation cycle.

(f) Data reduction program (DRC) - This program uses the flow tag to time-aline the actual flight telemetry data so that more accurate comparisons of this data with the reconstructed data can be made. The flow tag identifies the section of the math flow in which the DAS frame change occurs, and quantities which have not yet been calculated in the computation cycle are reverse time-tagged with one of two constant times; 0.616 seconds during retrofire, and 0.880 seconds from 400 000 ft on.

These two times are best estimates of the average computation cycle lengths for the two segments of the math flow involved; since the actual computation cycle varies somewhat about these averages, some error in time-alinement still exists, and cannot be further reduced or eliminated.

3.3 Reasons for Differences

This section presents a discussion of the factors which cause differences between the reconstructed data and the actual flight data. Some of these factors will continue to apply for future flights, and make a bit-for-bit reconstruction very difficult, if not impossible.

(a) Preretrofire limit cycling - For 10 seconds prior to retrofire, the computer accumulates platform pulses for use in the first computation cycle following retrofire. In the preretrofire countdown loop the accelerometers are read every 0.156 seconds, but come out over telemetry only every 2.4 seconds. Therefore, there is some uncertainty as to the exact values of the summed accelerations at the start of the 10-second countdown, and this uncertainty makes it impossible to determine with any confidence the exact number of pulses accumulated during the countdown loop. In the worst case limit cycling can cause an uncertainty of up to 5 pulses on each axis.

(b) Pulse distribution during retrofire - Linear interpolation was used to smooth the accelerometer outputs between telemetry frames. If retrofire attitude is held constant, and if the four retrorockets fire perfectly in sequence, linear interpolation produces negligible error. However, the telemetry data indicates a considerable amount of pitching and yawing during retrofire, coupled with a possibility that some delays may have existed between the end of burning of one jet and the start of the next. The contributions of these effects are no doubt small, but certainly make exact duplication of the telemetry data impossible.

(c) Reverse time-tagging - The telemetry data was time-alined by the DRC program described in section 3.2. The discussion in that section implies that variations in computation cycle length cause small errors in reverse time-tagging, which in turn make exact comparison with the reconstructed data impossible.

(d) Computation cycle time calculation - Very small differences will exist between the reconstructed data and the telemetry data, due to the method of calculating computation cycle times to be used by the OPS program. (The error introduced is negligible for purposes of the reconstruction, but is mentioned because it makes exact bit-for-bit reconstruction impossible.) The method is as follows:

Consider two successive DAS time t_1 and t_2. The difference $(t_2 - t_1)$ is first tested to establish the number of computation cycles between the two times, called CN. Then the average computation cycle time, without a frame change, is calculated from

$$\overline{\Delta t} = \frac{(t_2 - t_1) - 0.073}{CN}$$

where 0.073 second is the time required for a frame change. Then the first computation cycle of the group is given a time of $(\overline{\Delta t} + 0.073)$ seconds, and all the remaining ones except the last a time $\overline{\Delta t}$. The last computation cycle is determined by the difference $(t_2 - t_1)$ minus the sum of the preceding times in order to assure no accumulated time error.

(e) Initial condition uncertainty - The data used by the reconstruction program as initial conditions has been converted from octal to decimal. The decimal numbers were then converted back to octal again prior to being loaded into the program. It is possible that the double conversion may have resulted in one bit being gained or lost, so that the initial conditions used by the reconstruction program may have differed from those used by the flight GDC by as much as 256 ft in position and 0.25 fps in velocity.

This problem can be avoided in the future if it is found possible to obtain the exact octal values of the initial conditions transmitted to the spacecraft via the DCS.

3.4 Conclusions and Recommendations

This report shows that the GT-3 trajectory has been reproduced with a total position error of approximately 600 ft, and a total velocity error of approximately 0.5 fps. These errors are considered to be small, and have been attributed to known causes. If future missions are to be reconstructed in a similar fashion, it would be desirable to establish sensitivity coefficients to verify that the postulated error sources generate dispersions consistent with those observed. A small study using the FORTRAN six-degrees-of-freedom program would be sufficient to generate the required sensitivity coefficients.

The largest source of difficulty encountered in the reconstruction attempt was in the area of establishing key program break-points, mainly the beginning and the end of retrofire. For future programs it should be possible to automate the procedure for establishing these key times. It is recommended that some thought be given to this matter before future reconstructions are begun.

TABLE 3-I.- DCS QUANTITIES USED IN FLIGHT RECONSTRUCTION

X_{ER} =	-17 497 200 ft	K_{X3} =	0.0000586 ft/sec/pulse
Y_{ER} =	4 318 800 ft	K_{Y1} =	0.0000592 ft/sec/pulse
Z_{ER} =	11 510 700 ft	K_{Y2} =	0.00003415 ft/sec/pulse
$\dot{X}_{ER}$ =	-5 842.5 fps	K_{Y3} =	0.0974979 ft/sec/pulse
$\dot{Y}_{ER}$ =	-24 928.2 fps	K_{Z1} =	0.0000442 ft/sec/pulse
$\dot{Z}_{ER}$ =	246.6 fps	K_{Z2} =	-0.0902948 ft/sec/pulse
ϕ_T =	21.89° N	K_{Z3} =	0.0001366 ft/sec/pulse
θ_T =	69.88° W	K_{X4} =	-0.2618 pulse/sec
KACCT =	5.7	K_{Y4} =	0.230002 pulse/sec
$\Delta\theta$ =	74.88°	K_{Z4} =	0.223328 pulse/sec
K_{X1} =	0.1000975 ft/sec/pulse	KBA =	0 deg
K_{X2} =	0.0001598 ft/sec/pulse		

TABLE 3-II.- COMPARISON OF GT-3 TELEMETRY DATA (T/M) WITH RECONSTRUCTED DATA (R/C)

Parameter	End of retrofire (LO+631.922 sec)		S/C at 400 000 ft (LO+826.000 sec)		Initiation of guidance (LO+1063.125 sec)		After guidance cutoff (LO+1372.875 sec)	
	T/M	R/C	T/M	R/C	T/M	R/C	T/M	R/C
r_s	21 370 920	21 370 915	21 300 572	21 300 327	21 174 592	21 174 263	20 923 920	20 923 527
V_E	23 979.511	23 979.229	24 071.574	24 071.514	24 035.929	24 035 992	1 082.195	1 082.246
γ	-0.6595	-0.6595	-1.0531	-1.0538	-1.4461	-1.4471	-76.4985	-76.4850
ϕ	32.5319	32.5321	31.1590	31.1592	27.0584	27.0591	22.3527	22.3536
θ	170.9453	170.9428	-173.5176	-173.5175	-155.4826	-155.4840	-142.3766	-142.3776
ψ_E	91.8726	91.8712	100.5809	100.5807	100.0119	110.0112	147.8728	147.8995
R_T			1 687.683	1 688.422	763.207	763.015	60.654	60.441
R_C			-39.760	-39.728	-15.943	-15.926	30.204	30.876
ψ_T			101.9307	101.9298	111.2089	111.2070	117.1872	117.1497
D					7.9919	7.9927	4.4598	4.4577
R_P					653.437	653.344	-3.324	-3.328
$R_N - R_P$					110.277	109.504	61.958	61.959
B_c					33.2939	33.2963	0.00	0.3900

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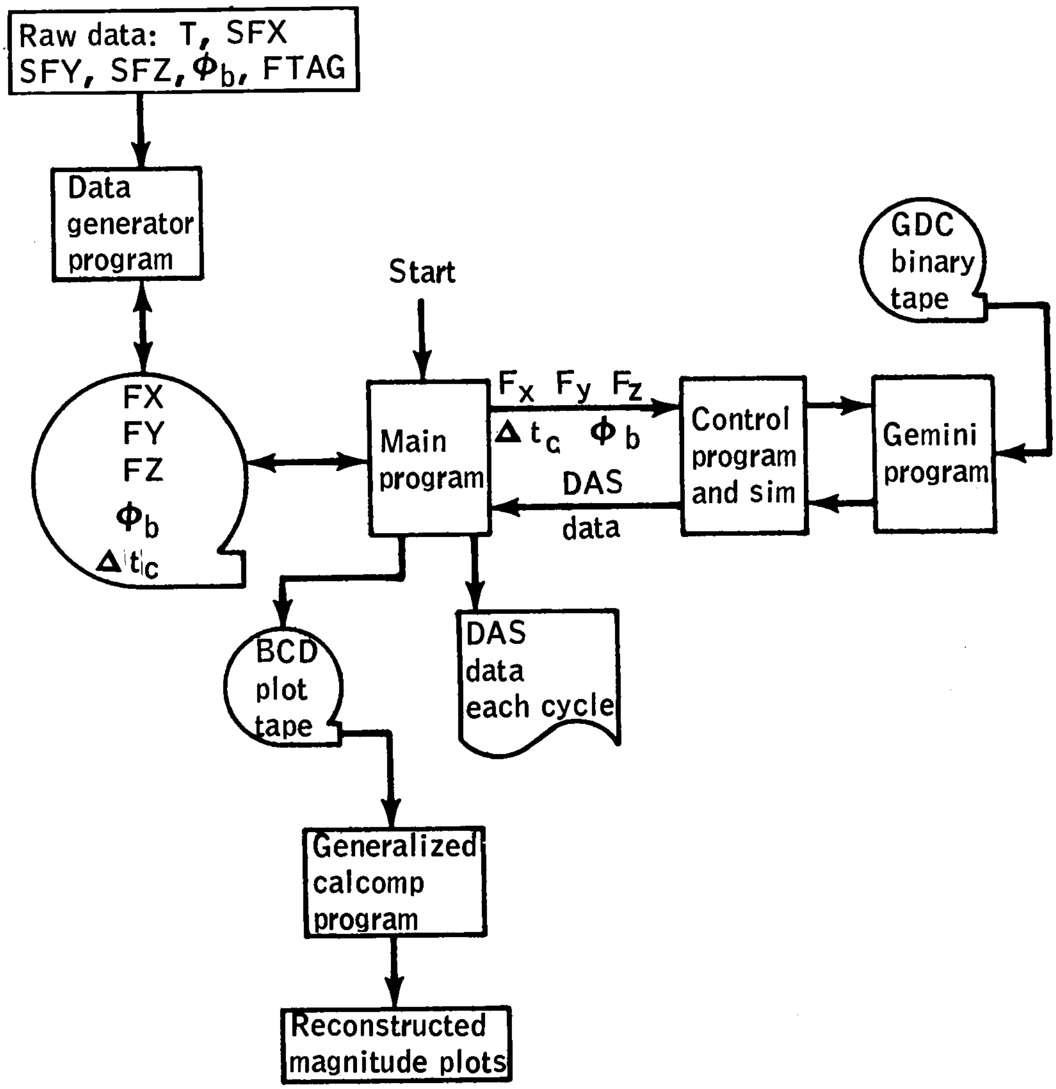

Figure 3-1.- Reentry mission reconstruction program.

4.0 REFERENCES

1. Gemini Operational Program MF-3 MOD I Flow Tag Document, dated February 17, 1965, IBM No. 65-542-01A.

2. Gemini GT-2 Ascent Post-Flight Analysis Report, dated February 12, 1965, IBM C.D. No. 3-260-6077.

3. Gemini GT-3 Ascent Predicted Performance Report, dated March 5, 1965, IBM C.D. No. 3-260-6086.

4. Gemini Ascent Guidance Time Line Analysis for GT-2, dated July 9, 1964, IBM C.D. No. 3-260-6022.